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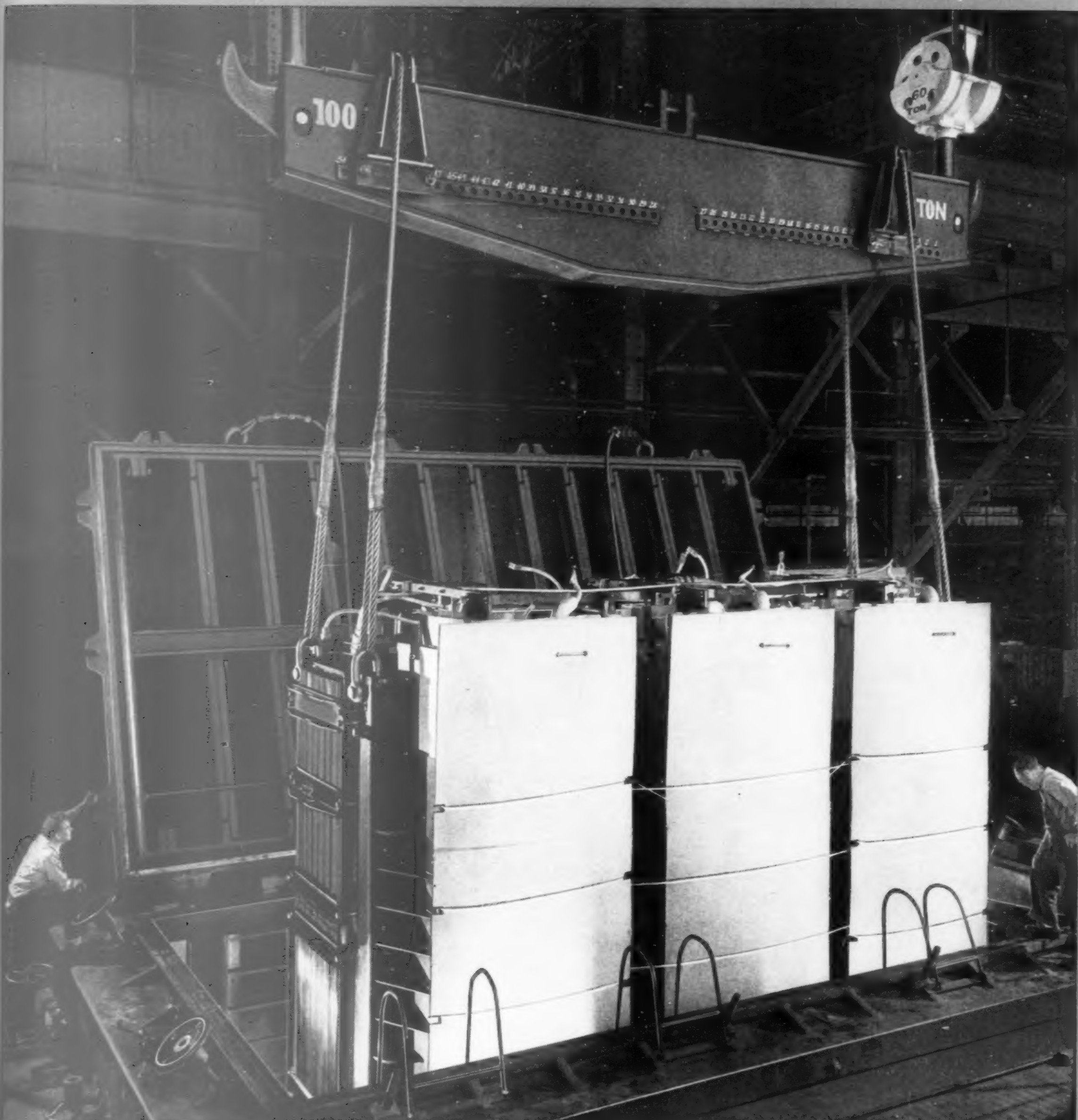
2ND QUARTER 1954

Electrical REVIEW



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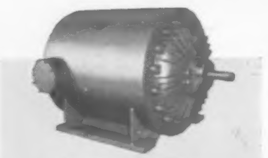

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Electrical REVIEW

THE COVER

LOSE WEIGHT TO LIVE LONGER — Into the vacuum tank goes this 150,000-kva three-phase autotransformer core and coil assembly where it will lose nearly three-quarter ton of life-destroying water. Pumps working day and night to maintain high vacuum will carry away moisture as water vapor and keep the tank interior arid . . . dry. After its dielectric materials have been dehydrated, this 122-ton core and coil assembly will be immersed in oil in its own tank.

A-C Staff Photo by M. Durante

Allis-Chalmers

ELECTRICAL REVIEW

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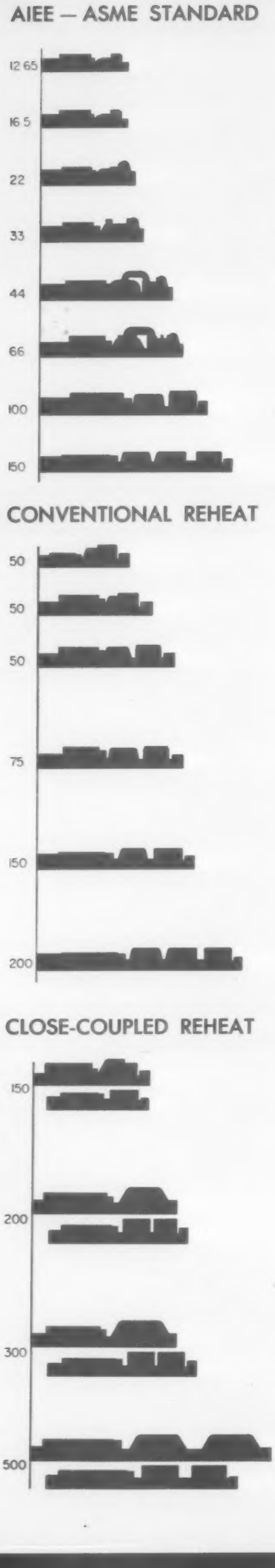

Today's Trends and TOMORROW'S TURBINES

by **C. D. WILSON**
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Steam Turbine Design
and
E. P. HANSEN
Steam Turbine Section
Allis-Chalmers Mfg. Co.

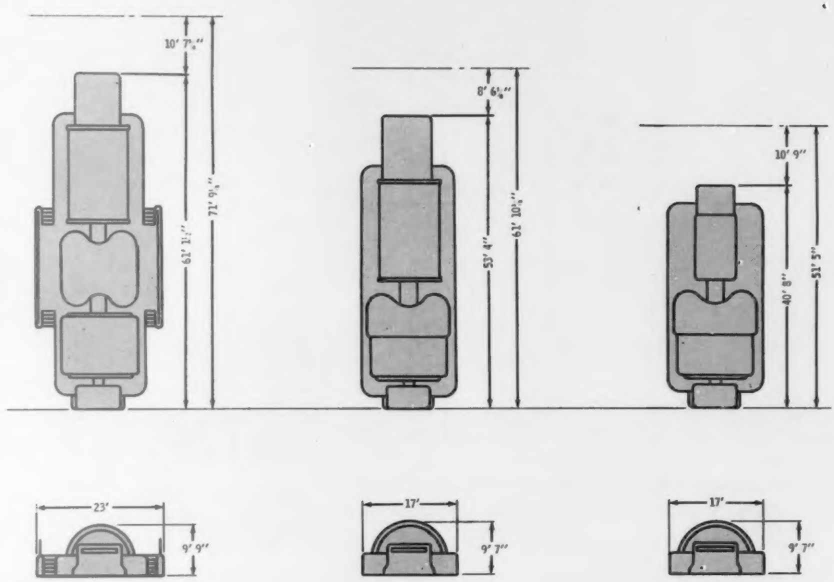
Unprecedented power progress today depends on high capability reheat turbines. Trend is toward better performance, compact designs.

ODAY, POWER PLANTS using steam turbines as prime movers constitute approximately 73 percent of the total electric generating capacity in this country. According to Federal Power Commission reports, the total capacity is now close to 110,000,000 kw, and this is presently being extended at a rate approaching 10,000,000 kw per year. Steam turbines being installed to meet this rapid yearly increase indicate several significant design trends.

The most important trends include: development of close-coupled cross-compound turbines for large capability applications; rapid increase in size of available 3600-rpm tandem machines; and widespread application of reheat to improve turbine performance. Also, special attention is being given to the use of optimum size exhausts for reducing leaving loss and to the development of more compact machines to obtain the benefits of reduced investment in building and foundations.

Comparative size and appearance of units developed to satisfy present-day requirements can be visualized from the silhouettes shown in Figure 1. The complete line of AIEE-ASME preferred standard units are at the top. Various arrangements which broaden the range of 3600-rpm tandem and single-cylinder units, including reheat units of smaller and larger capability, more compact designs, and machines having new and advanced features not now covered by the standards, are shown in the center. At the bottom, various arrangements of the close-coupled reheat cross-compound units in sizes ranging from 150 mw to 500 mw are indicated. The first close-coupled cross-compound unit was placed in service in 1953.

SILHOUETTES TO SCALE indicate relative size and appearance of steam turbine generator units available today in ratings from 12.65 mw to 500 mw. **(FIG. 1)**



TWO TRENDS—reheat for 50 mw — possible physical size reductions. **(FIGURE 2)**

Reheat for smaller turbines

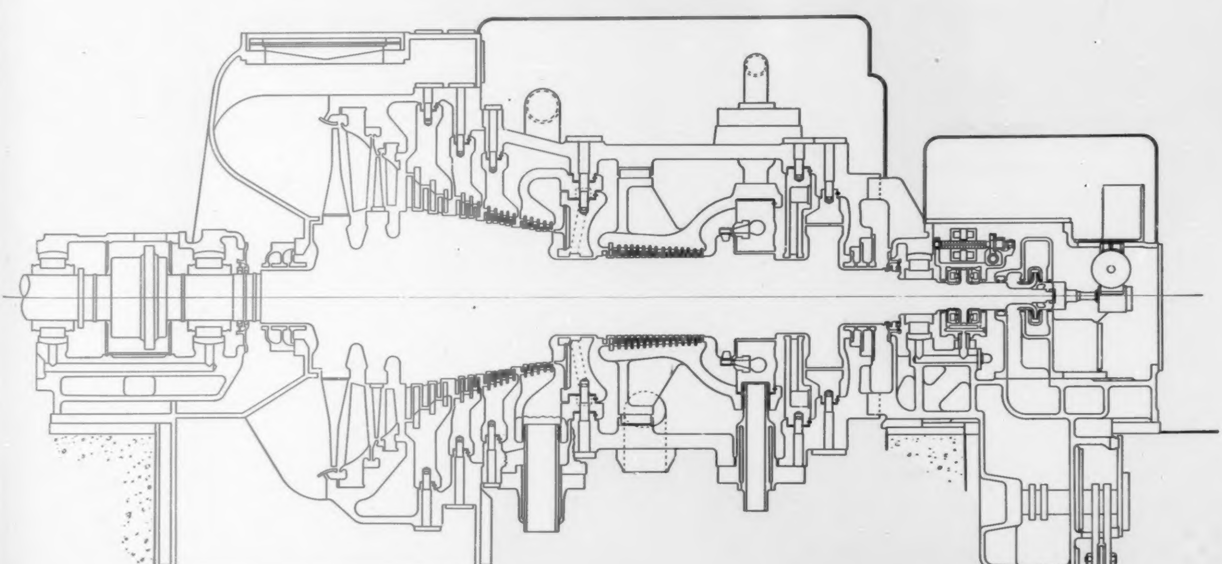
Three 50-mw reheat machines are shown as silhouettes and indicate distinct trends. One trend is toward the use of reheat to get improved performance in units of smaller capability. Another trend is toward more compact units which will occupy less floor space in the turbine room.

Reheat applied to a unit of this size results in a performance gain of approximately 4½ percent when compared to a non-reheat unit of the same capability operating with the same initial steam conditions.

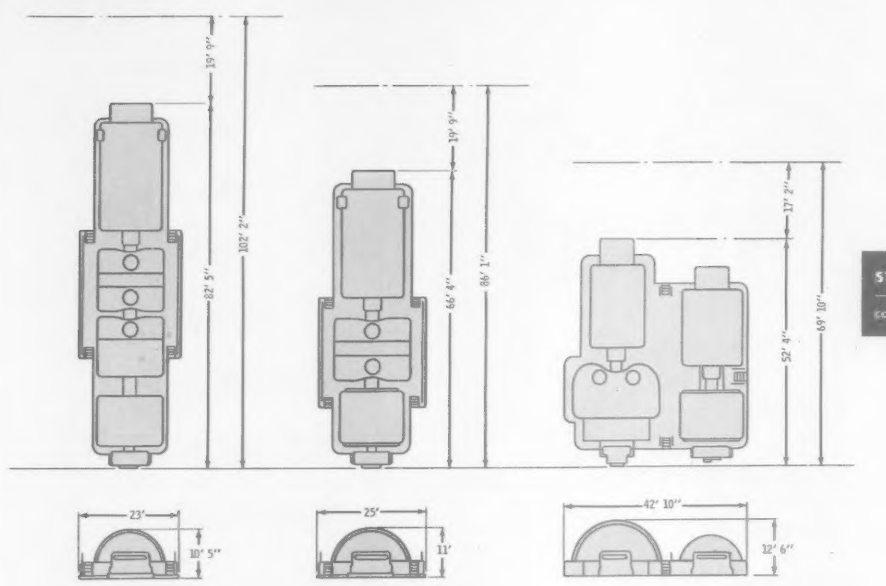
The longest unit shown in Figure 2 is a 50-mw tandem reheat turbine with a double-flow low pressure element using 18-inch exhaust blades, coupled to a conventional hydrogen-cooled generator.

Overall length of a 50-mw reheat machine can be reduced to 87 percent of the tandem reheat machine by using a single-cylinder turbine with the same generator. This saving in length is obtained at a slight sacrifice in performance due to smaller exhaust blade area, but the net gain over the non-reheat unit is still appreciable.

When justified by economic considerations, the shortest unit in Figure 2 shows what can be done to achieve a very



UNIDIRECTIONAL steam flow, 23-inch exhaust blades and separate mechanically guided, thermally free nozzle ring characterize this compact 50-mw single-cylinder reheat turbine. **(FIG. 3)**

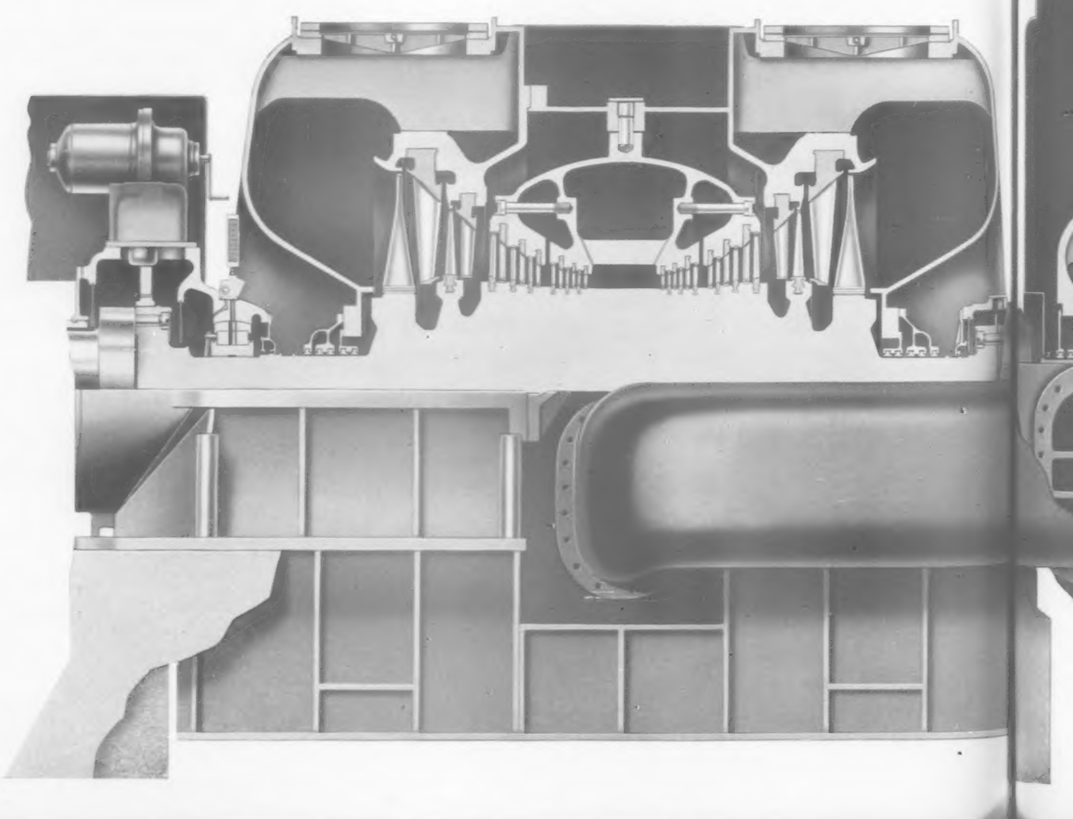


STUDY IN 150-mw reheat designs — two tandems and the new close-coupled cross-compound. **(FIG. 4)**

compact 50-mw reheat machine. This combination of a fully supercharged hydrogen-cooled generator with the single-cylinder reheat turbine results in a machine that is only 67 percent of the length of the 50-mw tandem reheat unit and is even shorter than the 22-mw, non-reheat preferred standard machine.

The single-cylinder 50-mw reheat turbine shown in Figure 3 is built with unidirectional steam flow on a single shaft and uses a single exhaust flow with 23-inch exhaust blades. Stationary blading in the high pressure section, between the primary inlet and the reheat point, is carried in a double casing. This machine was designed for 1450 psi, 1000 F inlet steam with 1000 F reheat.

To isolate the high inlet temperatures from both the inner and outer casings, the nozzle chests are in the form of a separate guided ring which is free to expand thermally. This avoids uneven temperature distribution and possible distortion in both inner and outer turbine casings



when operating at light load with partial admission. A saving in length is obtained by installing the high pressure balance piston seal strips in the inner bore of the nozzle chest ring, and differential expansions are minimized by anchoring stationary and moving parts in a manner that allows them to expand together in the same direction.

The control valve manifold for this machine is built as a separate element and is located to the side of the unit, below the operating floor. Reheat control valves, also below the turbine floor, are installed in connecting steam lines close to the turbine, but sufficiently removed to permit complete accessibility to all parts.

Tandem vs. close-coupled cross-compound

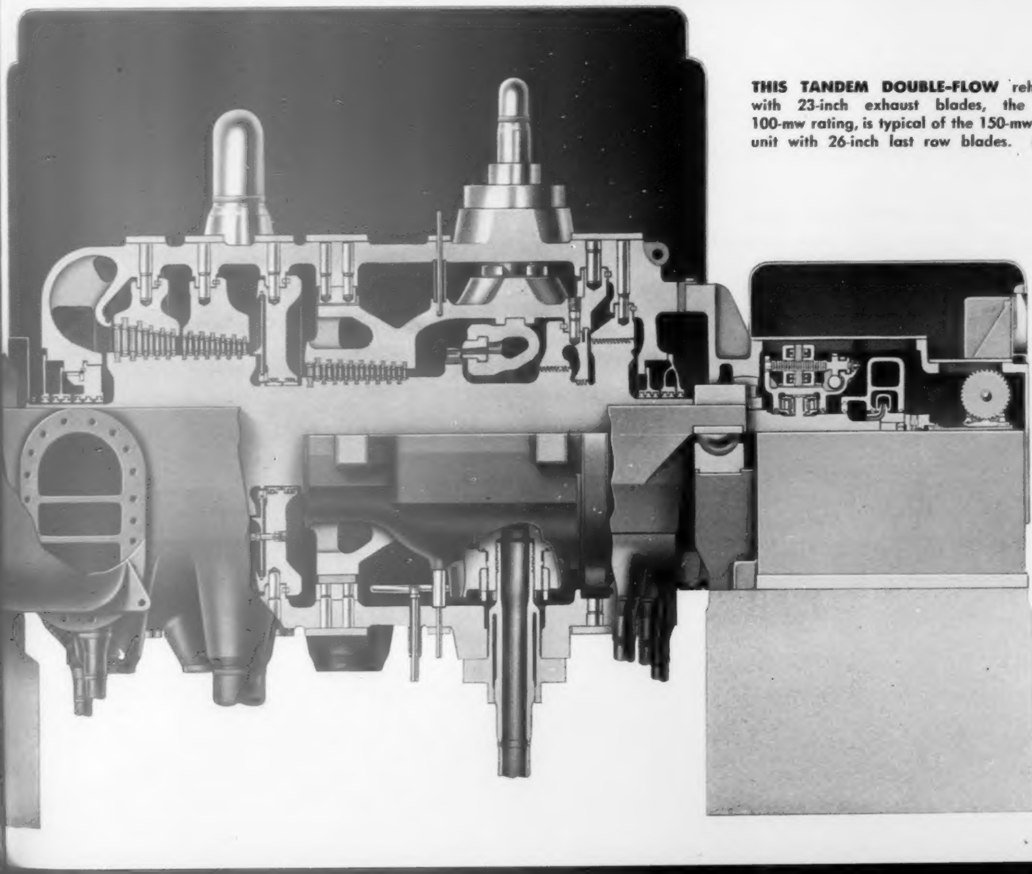
Overall outline dimensions for three different types of 150-mw reheat machines that have been developed for high, medium, and low exhaust pressures are illustrated in Figure 4. Each type has advantages and limitations which have to be evaluated in determining the one most desirable for a particular application. The center machine, a 3600-rpm double-flow exhaust tandem turbine using 26-inch exhaust blades, has the advantages of shorter length and lower investment. On the other hand, the longer preferred standard machine, using triple flow with 23-inch blades, has approximately 22 percent more exhaust area, resulting in slightly better performance for the high load range with exhaust pressure of 1½ inches or better. For applications where exhaust pressures are not so favorable, the shorter machine will be superior.

MODERN 75-MW, TANDEM, at Rock River Station of Wisconsin Power and Light Company, is typical in appearance of both 100-mw and 150-mw tandem double-flow reheat units. **(FIGURE 6)**

Most compact of the three arrangements is the close-coupled cross-compound machine. This machine can be built with optimum size exhaust to obtain the benefits of minimum leaving loss in applications where very low exhaust pressures (less than 1½ inches) are available.

The cutaway drawing in Figure 5 shows a 100-mw tandem reheat turbine with double-flow 23-inch exhaust blades. This machine is similar in design to the larger 150-mw reheat turbine which uses double-flow 26-inch exhaust blades. Unidirectional steam flow and a reheat diaphragm designed to avoid thermal distortion provide a turbine arrangement that has proved to be inherently stable under all conditions of operation.

Typical in general appearance of all these tandem double-flow machines is the 75-mw capability turbine



THIS TANDEM DOUBLE-FLOW reheat turbine with 23-inch exhaust blades, the AIEE-ASME 100-mw rating, is typical of the 150-mw double-flow unit with 26-inch last row blades. **(FIGURE 5)**

shown in Figure 6. This unit was provided with longer than normal last row blades because of the low exhaust pressure available at this location.

This installation also indicates a trend toward centralizing operating controls mounted on the unit. All major turbine controls are grouped on an indirect-lighted panel recessed in the forward pedestal, and all hydrogen seal instrumentation is centralized on a small panel on the side of the generator.

Large 3600-rpm tandem units

As central stations continue to grow in capacity, economic advantages have pointed to the development of individual machines with capabilities far in excess of anything considered practical just a few years ago. A cross section of a turbine that is typical of the large capability 3600-rpm tandem reheat turbines now available is shown in Figure 7. This machine is a three-cylinder tandem unit using three exhaust flows of 26-inch blades. It can be built with capabilities ranging from 187.5 to 250 mw, depending on available exhaust pressure.

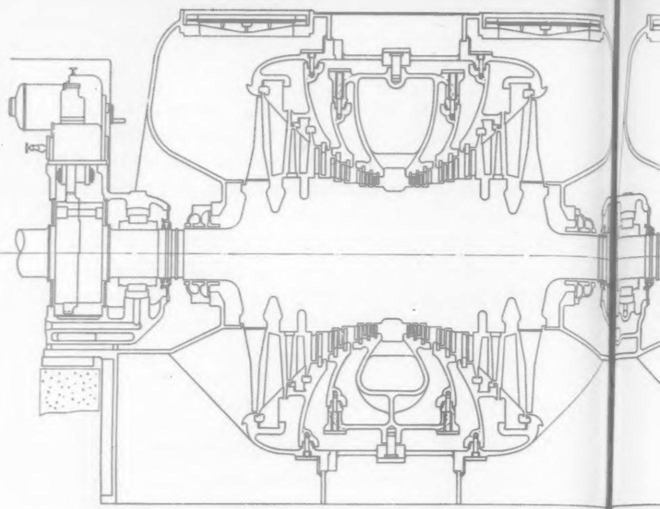
Thrust of both turbine and generator shafts is carried by a single thrust bearing located between the high pressure and the intermediate pressure turbines. This construction, with opposed steam flow in the two turbines, minimizes axial displacements between stationary and moving parts that result from temperature differentials between the turbine casing and shafts. Anchor points between inner and outer casings and between casings and pedestals are carefully located to obtain stable operation with minimum change in axial clearance between cold non-operating and hot operating conditions.

In this design, chrome-molybdenum ferritic materials are used for temperatures up to and including 1050 F. High temperatures at the primary and reheat inlets are isolated from the main bodies of the turbine casings, and for temperatures higher than 1050 F, the ferritic material is replaced by ausenitic material in parts exposed to the highest temperature.

Close-coupled cross-compound types

Various sizes of close-coupled cross-compound turbines developed to satisfy the trend toward very large machines are shown in silhouette in the lower portion of Figure 1. The large exhaust area required for superior performance on turbines of large capability is provided by the 1800-rpm low pressure turbine, while the close-coupled arrangement makes possible large capability units of very compact size.

Overall dimensions of a 250-mw, close-coupled cross-compound machine are compared with a smaller capability, 200-mw, 3600-rpm tandem unit in Figure 8. Cross-compound units in this size range can be built with larger exhaust area and are capable of much better performance than corresponding 3600-rpm tandem machines with exhaust pressures normally encountered in most localities. Because of its compactness, either transverse or longitudinal installation of close-coupled cross-compound units can be made in the turbine room with minimum crane span and within the space limitations of the boiler. The end result is a smaller building with smaller foundations.



The first close-coupled cross-compound machine was placed in service in 1953. This machine, shown in Figure 9, utilizes 40-inch exhaust blades and is typical of the close-coupled cross-compound design. Machines of this type can be built in very large sizes. While the particular unit shown is rated at 120 mw, it is designed to operate with ½-inch exhaust pressure. For 1-inch exhaust pressure, a low pressure turbine of the same size could be efficiently applied to a 250-mw unit. Units of this type can be built in all sizes up to 500 mw, and the large exhaust areas available with the 1800-rpm low pressure turbine make high performance levels possible on these large machines.

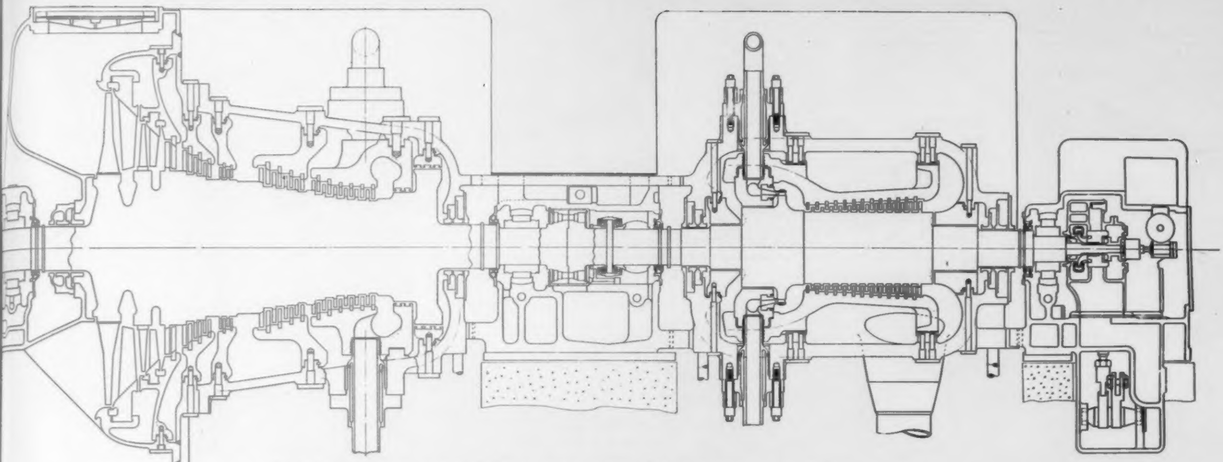
Improved performance—past and future

The utilization of large exhaust areas to obtain the benefits of reduced leaving loss and the application of reheat are the major factors which have contributed to improved turbine performance. These, plus numerous refinements to improve internal turbine efficiency, are bringing the actual obtainable heat rates close to the maximum that can be economically justified for present-day steam conditions.

Further progress in the trend toward improved station performance requires consideration of higher initial steam conditions and the use of multiple reheat. The present-day trend in turbine design is in that direction.

Maximum steam temperature is governed by the high temperature properties of available materials. At the present time this appears to be in the neighborhood of 1100 to 1150 F. Increasing pressures above present-day maximums will require a transition into the supercritical region because of steam generation problems at the critical pressure. Application of higher initial steam conditions and the addition of double reheat can provide performance gains somewhat larger than those realized when single reheat was added to the regenerative cycle.

Since the smaller specific volume of steam at supercritical pressures makes it necessary to increase steam flow



LARGE TANDEM units in ratings from 187.5 to 250 mw at 3600 rpm use this three-cylinder triple-flow construction with 26-inch exhaust blades. **(FIGURE 7)**

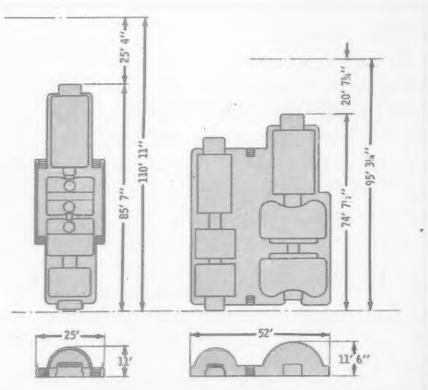
(and capability of the turbine) to obtain turbine proportions within the practical size limits required for high efficiency, supercritical pressure appears to be economically justified only in the larger units. Also, only units of large capability can economically justify the additional investment of more costly materials, more controls, piping, and auxiliary equipment.

In order to avoid excessive moisture in the exhaust, two stages of reheating are desirable when using supercritical pressures. The second stage of reheat also provides a performance gain of about 1½ percent over that of single reheat.

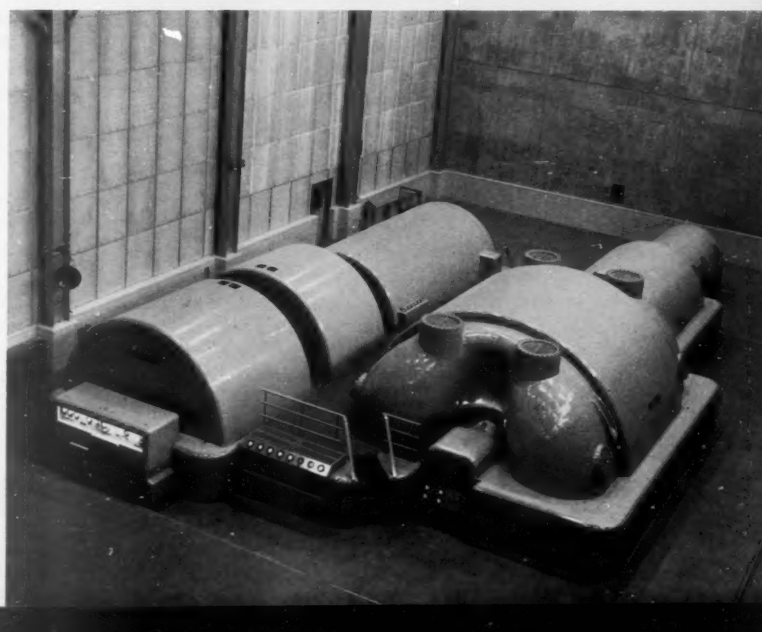
The trend in steam turbine development embraces a large number of factors, but those most important to utilities are related to the economics of power generation. To keep ahead of the large yearly increase in the use of power, utilities are adding generating capacity in large blocks. This has placed emphasis on large units which require large buildings and heavy foundations. Reduction in turbine weight and dimensions sufficient to be reflected in the cost of power plant construction is of paramount importance.

Units of large capability are growing in popularity because they are lower in cost per kilowatt of capacity and can justify special added features, such as higher inlet pressures and temperatures, reheating, and optimum size exhausts. The turbine builders are making a concerted effort to supply the most efficient equipment possible at no sacrifice in reliability.

Continuing demand for higher turbine efficiency requires a further increase in steam temperature to obtain the greater available energy necessary for improved performance. This, in turn, requires the development of new materials suitable for these higher temperatures. If suitable materials are not available when needed, it may be necessary to design the components exposed to highest temperatures as expendable items to be replaced after a predetermined period of operation. All of these factors require careful consideration when designing and building tomorrow's turbines.

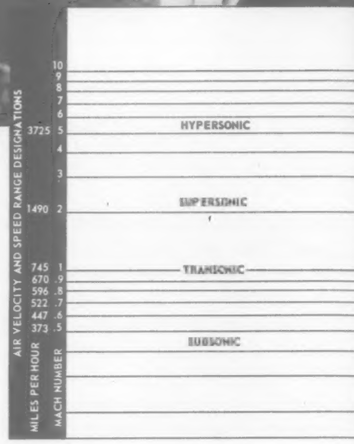


CLOSE-COUPLED cross-compound 250-mw compared to tandem triple-flow 200-mw unit—a study in trends for the largest ratings. **(FIGURE 8)**



INSTALLED LAST YEAR, the first close-coupled unit, rated 120 mw, is in service at Wisconsin Electric Power Company's Oak Creek Station. **(FIGURE 9)**

TWIN DRIVE Designed for New Transonic Wind Tunnel



by **M. F. GAY**
Motor and Generator Section
and
ELROY BOENING
Electrical Control Section
Allis-Chalmers Mfg. Co.

ORCING AIR through a 7 by 10 foot test section at transonic speeds . . . carrying model aircraft through the sound barrier by controlling fan speed . . . accurately maintaining a given rpm for any required time — these were design requirements of the two 12,000-hp variable speed drives for the Navy's new wind tunnel at David Taylor Model Basin, Carderock, Maryland.

Designing this twin drive was further complicated by two other factors. First, although power is obtained from a very large system, location of this site on the power lines dictated that heavy starting current to motors be avoided and load increases or decreases, except under emergency conditions, be gradual.

Second, no design or operating data existed for the two contrarotating multibladed fans used to circulate air within the tunnel. Consequently, their efficient use imposed a number of requirements on the drive. These fans, shown in Figure 1, were originally built for a proposed German wind tunnel of advanced design, but had never been operated.

By designing the drive and its control for extremely accurate speed regulation — 0.1 percent of 705 rpm — two desired results were obtained. First, the contrarotating fans may be operated over a wide range of speeds — any critical speed points that might exist are avoided. Second, small differentials in operating speeds between the two fans can be maintained if necessary.

Drive selected meets requirements

Before equipment was specified, several types of drives were considered. The drive finally selected — actually two identical drives, one for each of the contrarotating fans — complied with all operating conditions and was considered to be most economical.

Each drive consists of a unity power factor synchronous motor driving its fan through an eddy-current magnetic coupling, and a short-time rated wound-rotor induction motor to accelerate the synchronous motor rotor as well as the input member of the eddy-current magnetic coupling.

A liquid rheostat in the rotor circuit of the starting motor adjusts automatically during acceleration to maintain a constant accelerating torque until the speed of the starting motor approaches the synchronous speed of the drive motor. At near synchronous speed, the control of the wound-rotor motor is automatically adjusted by controlling the resistance of the liquid rheostat through a *Synchro-Operator*.

This automatic synchronizing device adjusts the speed of the wound-rotor motor so that the frequency and phase

AIR IS DRIVEN by this 19-foot dual fan section — the air velocity controlled by fan speed. **(FIGURE 1)**

angle of the synchronous motor exactly match the frequency and phase angle of the power supply. At that moment it initiates the closing of the circuit breaker connecting the stator of the synchronous motor to the power supply.

Location of the drive equipment, its general arrangement and functional relationship are indicated by the wind tunnel diagram, Figure 2. Each of the two drive motors is a 12,000-hp, 720-rpm, 1.0 power factor, 13,200-volt, three-phase, 60-cycle, salient-pole synchronous machine having a 15 percent service factor on continuous duty, giving a continuous service factor rating of 13,800 hp. One end of the synchronous motor is coupled to a water-cooled eddy-current magnetic coupling. Incorporated with the coupling is an eddy-current magnetic brake and a pneumatically operated mechanical holding brake. At the other end of the synchronous motor there is a 350-hp, 900-rpm, 2300-volt, three-phase, 60-cycle, 1/8 hour rated, wound-rotor induction starting motor. The other major items in each drive consist of a liquid rheostat and control, an excitation motor-generator set and eddy-current coupling control. A single operating control console and switchgear serve both drives.

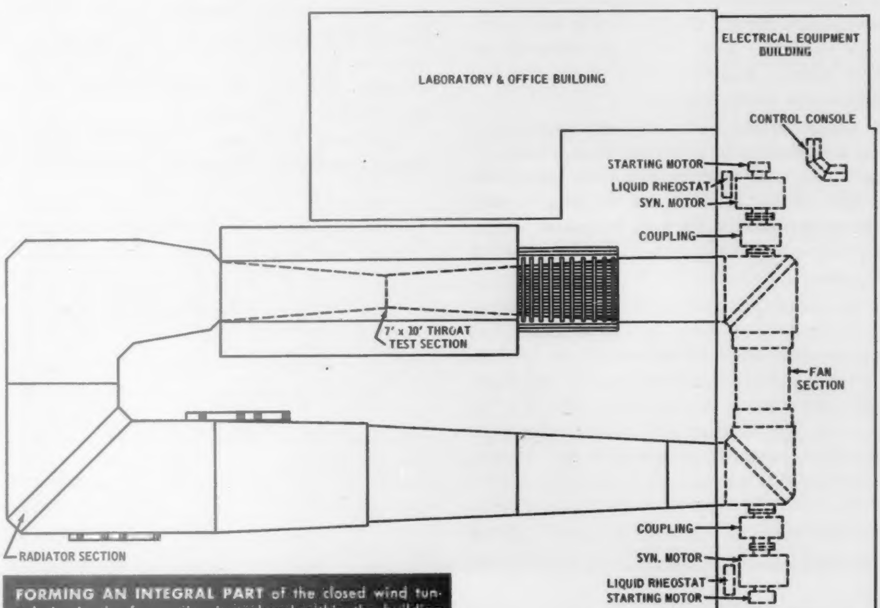
In addition to complying with the required speed control accuracy, the rate of response of the drive to desired speed changes is fast. The fast response results from the small time constant of the eddy-current magnetic coupling which controls the final output speed of the drive, and from the use of a rotating amplifier excitation system in conjunction with the electronic control for the eddy-current magnetic coupling.

If either of the two fans attempts to overspeed, because of recirculating air, power from the fan can be fed through the magnetic coupling to the synchronous motor which acts as a generator to feed power back into the power supply. This prevents a fan from operating at more than just a few percent above its full-load speed.

The eddy-current magnetic coupling reduces speed by increasing slip. Since the fan load varies as the cube of speed, this slip loss reaches its maximum of only about 17 percent of the drive's rating at 66⅔ percent speed. Despite this slip loss, the total annual operating cost of this drive is less than, or comparable to, that of the other types of drives considered for this installation.

Line disturbances are small

Motor starting current is kept to a minimum by using a wound-rotor starting motor rated only 350 hp. Since only the synchronous motor rotor and the input member of the eddy-current magnetic coupling are accelerated, this rating is adequate. The output member of the eddy-current magnetic coupling and the coupled fan remain stationary during the acceleration of the drive motor.



FORMING AN INTEGRAL PART of the closed wind tunnel circuit, the fan section is enclosed within the building that houses the drive and control equipment. **(FIGURE 2)**

BOTH DRIVES are controlled during acceleration from this console located in the electrical equipment building, see Figure 2. **(FIGURE 3)**

Maximum liquid rheostat resistance is inserted in the rotor circuit prior to starting the motor. As a result, starting current is very small compared to the total installed horsepower of the drive. Automatic synchronization of the drive to the line is accomplished at the time of minimum kva interchange between the motor and power supply. The actual line disturbance is only a very small fraction of the rated full-load kva input to the motor.

After synchronization, the operator at the control console, shown in Figure 3, presses the excitation pushbutton, which permits the fan speed to be varied from the remote control station near the tunnel. The location of the remote control is such that the model and tunnel test instruments may be conveniently observed by the operator.

Drive motors supply reactive kva

This drive lends itself particularly well to the use of the salient-pole synchronous motors as synchronous condensers to improve characteristics of the power system during periods when the tunnel is not in operation. Either one or both of the synchronous motors can be floated on the line, with the output member of the corresponding eddy-current coupling stationary. The excitation of the synchronous machine is then controlled to supply the required amount of reactive kva within the permissible rotor temperatures of the machine. Even during operation of the fans at reduced speed, a limited amount of reactive kva can be supplied to the power system.

Breakaway torque necessary to start the synchronous motor rotating is minimized by a high pressure lubrication system installed at each of the drive motor bearings to lift the rotor and float it on an oil film. Interlocking between the oil pressure system and the starting equipment assures sufficient oil pressure to lift the rotor before the starting motor is energized.

A separate recirculating system for each drive, incorporating a lube oil pump with drive motor, oil cooler, and external sump, provides flood lubrication of the synchronous motor bearings. Each of the bearings is a self-aligning, spherically seated sleeve bearing with two oil rings. The oil rings alone will lubricate the bearing adequately during an emergency, since the oil sump in each bearing pedestal has enough thermal capacity to permit a normal stop without oil circulating through the external oil sump.

Operating temperature of each drive motor and its bearings is continuously monitored by thermocouple-type detectors having their sensing elements embedded in bearing babbitt and stator windings of the motor.

Construction simplifies inspection procedures

To simplify inspection and maintenance procedures, the synchronous motor is arranged for full stator shift without removable cross members in the base, stub shafts, or removable bearing pedestals. Both the motor base and shaft have sufficient length to permit moving the stator far enough laterally to fully expose the rotor. In this position, both stator coils and rotor field coils can be maintained or removed without disturbing the alignment of bearing pedestals and couplings.

The starting motor enclosure is of open self-ventilated construction. The rotor is pressed directly on a shaft extension of the 12,000-hp synchronous drive motor, and its stator is mounted on the same base that mounts the magnetic coupling and drive motor. A centrifugal speed limit switch is connected to the starting motor end of the shaft and set to operate at a speed slightly higher than the 720-rpm synchronous speed of the main drive motor.

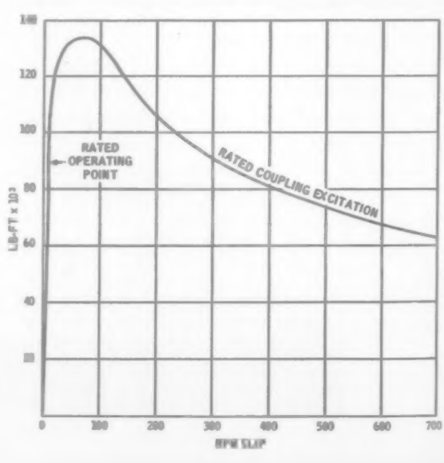
Control of acceleration for the wound-rotor starting motor is transferred from torque control to the automatic synchronizing device by a tachometer generator, mounted on the bearing pedestal between the starting motor and the drive motor. It is driven by a set of oil-immersed speed-increasing gears of suitable ratio.

Motors drive fans through magnetic couplings

Each of the magnetic couplings has two concentrically mounted independent rotating members. The inner member is driven by the synchronous motor, the outer member drives the fan. When the coupling is driven by the synchronous motor, the relative speed between the input and output members depends upon the amount of excitation supplied to the coils on the inner member and upon the load torque imposed by the fan. Pole pieces on the inner member influence the flux density in the outer member because of the speed differential between the two. This variation in flux density produces eddy currents which set up a magnetic flux, enabling the two magnetic fields to produce a torque. The resulting torque reaction results in the output member rotating.

The curve in Figure 4 shows the magnitude of the torque developed with rated excitation at various relative

TORQUE CURVE for the magnetic coupling at rated excitation is one of a family of similar excitation curves. **(FIGURE 4)**



speeds, or slip, between the two members. For every other value of excitation there is a corresponding torque curve. Output speed is selected and controlled by adjusting excitation so that the coupling slip-torque curve intersects the fan speed-torque curve at the desired speed.

Power losses resulting from this method of speed control are dissipated as heat through water introduced between the stationary housing and the outer member of the eddy-current coupling. Rate of cooling water flow is adjusted by a thermostatically controlled water-proportioning valve.

Other interesting components of the drive include: an eddy-current magnetic brake on the output member of the coupling to aid in decreasing fan speed when the coupling is de-energized; a pneumatically operated mechanical brake to hold the output member at standstill when necessary; and a governor generator on the magnetic coupling which develops an output voltage proportional to the output speed. This signal is used in the electronic control to hold the speed at any desired value.

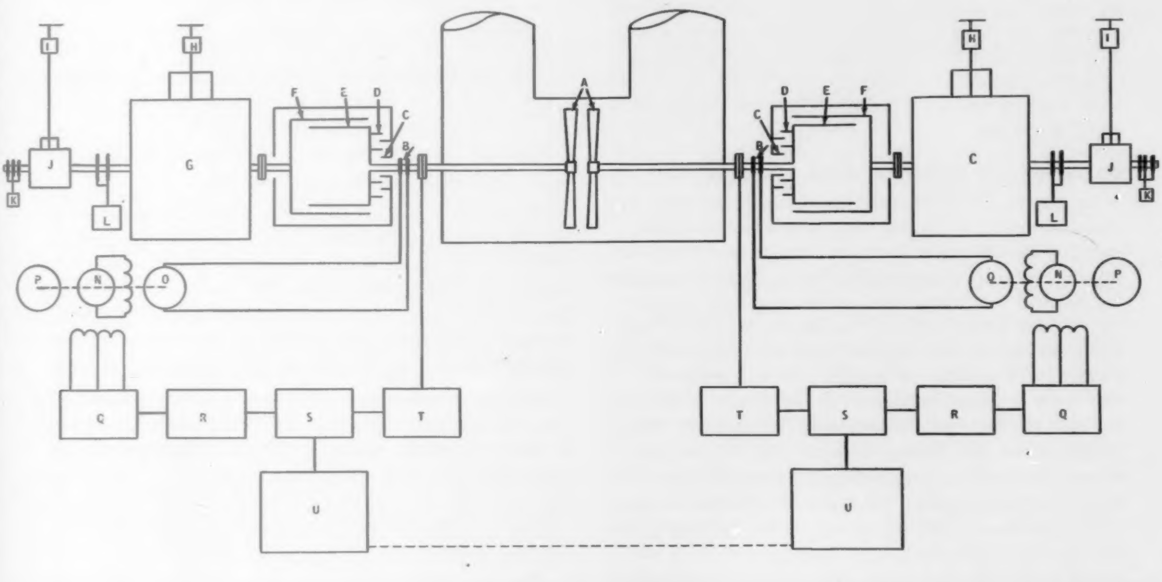
Speed is accurately controlled

As in most wind tunnel drives, precise speed control is an essential requirement. Close regulation of fan speed is obtained by electronically controlling the excitation of the eddy-current couplings. The 30-kw excitation required by each coupling is obtained from 30-kw exciters. They in turn have their excitation controlled by *Regulex* exciters and electronic speed regulators. The basic control scheme is shown in Figure 5.

The speed signal, proportional to fan speed, is obtained from a permanent magnet type alternator driven by the output shaft of the eddy-current coupling. The rectified and filtered alternator output is connected in series opposition to an electronically regulated reference supply which can be adjusted to any desired value by means of a speed-setting potentiometer rheostat. The resultant voltage is fed into an error amplifier, then to a power rectifier unit, and then to the two oppositely connected control windings of the rotating amplifier. One control winding causes the rotating amplifier voltage to increase, increasing the coupling excitation; while the other winding causes the voltage and coupling excitation to decrease. If a fan is rotating above or below the desired speed, the electronic speed regulator controls the coupling excitation to minimize the deviation and bring the fan speed to the desired value. Each fan has its own electronic speed regulator, complete with *Regulex* exciter and main exciter. Speeds of the two fans are coordinated by magnetically clutching their speed-setting potentiometer rheostats.

Protective system has unique feature

Adequate protection for the synchronous motors and wound-rotor starting motors is provided by metal-clad



(A) Contrarotating fans
(B) Coupling excitation slip rings
(C) Mechanical brake
(D) Eddy-current brake
(E) Coupling output member
(F) Coupling input member
(G) 12,000-hp synchronous motor
(H) Breaker for synchronous motor
(I) Breaker for starting motor
(J) 350-hp starting motor
(K) Liquid rheostat
(L) 75-kw drive motor field exciter
(N) *Regulex* exciter
(O) Coupling exciter
(P) 60-hp exciter drive motor
(Q) Power rectifier unit
(R) Error amplifier
(S) Comparison unit
(T) Speed signal rectifier and filter
(U) Electronic reference and speed-setting potentiometer

MAIN DRIVE and speed regulation equipment is indicated. Parts lettered *Q, R, S, T, U* comprise the electronic speed regulator. **(FIGURE 5)**

switchgear units. Oil circuit breakers, each having an interrupting capacity of 500,000 kva at 13,200 volts, supply power to the synchronous drive motors, while breakers rated 100,000 kva at 2300 volts supply the wound-rotor starting motors.

Relays are provided in the switchgear units to protect the synchronous motors against overload, low voltage, ground fault, open phase, phase unbalance, phase reversal, overheating of the windings, internal winding faults, and field failure. Protection for the wound-rotor starting motors is not so elaborate and consists only of overload, thermal, and phase reversal relays.

One unique feature of the protective equipment for these drives is the temperature-monitoring system. Twenty-five iron constantan thermocouples are strategically located inside the fan bearings, drive motor bearings, coupling bearings, and oil and water lines. Continuous rapid checking of these thermocouples detects any abnormal temperatures. Consisting of four basic units — a motor-driven scanning switch, a comparison unit, a detector unit, and an annunciator — the monitoring system checks ten thermocouples per second.

Twenty-five potentiometer-connected rheostats, paralleled to a regulated reference voltage, provide individually adjustable alarm points for each of the 25 thermocouples. Should the voltage of a thermocouple exceed the voltage of the comparison source when the scanning switch closes its circuit, the detector unit will function to pick up the necessary annunciator relay, give an alarm and shut down the drive. The detector unit consists of a vibrating reed converter for chopping the thermocouple voltage, a step-up transformer and a three-stage voltage amplifier. The monitoring system is designed so that it can be conveniently checked during operation of the drive without causing a shutdown.

Operating the transonic wind tunnel drive

When starting the drive, synchronization of the large synchronous motors to the line with an absolute minimum of electrical disturbance to the power system is accomplished by an automatic synchronizing device. All the separate functions of a synchroscope, synchronizer, and frequency matcher are performed by this one device, which accurately anticipates the inherent time lag required by the breaker to close after the control circuit is energized. It also gives a visual indication of the phase relationship between the line and the synchronous motor. To obtain proper phase relationship between the line and drive motor, the synchronizing device controls electrode position in a liquid rheostat, which in turn controls the speed of the wound-rotor starting motor. Since the liquid rheostat has an infinite number of speed points, it is ideally suited to the task of obtaining correct synchronizing speed in minimum time.

Operating procedure of the wind tunnel is best illustrated by a brief description of starting and stopping. Figure 5 shows the rotating equipment and main power connections involved in the starting procedure outlined below:

1 — Start up all the low voltage auxiliary equipment, such as electrolyte pump motors for liquid rheostats, low and high pressure lubricating pumps, vacuum oil pumps, air compressor for eddy-current couplings, and rotating amplifier sets.

2 — Check to see that all operating personnel are out of tunnel and tunnel doors are locked. Remove key from tunnel door, and insert in key interlock on control benchboard. (The main drive equipment cannot be started unless the key interlock switch is turned and all tunnel doors are locked in the closed position.)

3 — Start up the main exciter set.

4 — Close the starting motor breaker.

5 — The starting motor then accelerates under the control of the liquid rheostat. When synchronous speed of the 12,000-hp motor is approached, a speed-sensitive relay operates to close the field breaker of the synchronous motor automatically. As soon as the field breaker of the synchronous motor is energized, the synchronizing device controls the liquid rheostat to synchronize the voltage, frequency, and phase angle automatically. When the machine is in step with the line, the synchronizing device closes the breaker supplying the 12,000-hp synchronous motor. An auxiliary switch on the synchronous motor breaker then trips the starting motor breaker and sets up a sequence of operation which automatically returns the electrodes of the liquid rheostat to the starting or "all-resistance-in" position.

6 — Next the coupling excitation pushbutton is pressed. This completes the coupling excitation circuit and permits the fan to be started from the remote control station near the tunnel.

7 — Starting procedure steps 4, 5, and 6 are then repeated for the fan not yet started.

Normal stopping of the fans is accomplished by using the electronic speed control. Since stopping is gradual, power requirements decrease without causing objectionable sudden load variations on the power supply. After the fans have come to a stop, the coupling excitation contactor is opened and the synchronous motor breakers are tripped. The exciter sets and auxiliaries are then stopped.

Emergency stopping of the fans is accomplished by pressing the "stop" button at the remote control station or at the benchboard. This removes the excitation from the couplings and brings the fans to a stop. An eddy-current brake is used on each fan to reduce the stopping time. In addition, mechanical braking is automatically applied to the fans when a safe reduced speed is reached.

All requirements for close speed control — accurately maintained — and for minimum line disturbances are fulfilled by this drive at the Navy's newest and largest wind tunnel. By using the two 12,000-hp synchronous motors as synchronous condensers, this installation has actually improved the power factor of the distribution system supplying the Carderock area during those periods when the wind tunnel is not in actual use.

How to Find...

THE RIGHT SPOT FOR REGULATORS

by **R. D. OKERBERG**
Transformer Section
Allis-Chalmers Mfg. Co.

DISTRIBUTION REGULATOR PLACEMENT is not determined by low voltage alone but also by load conditions on the line. Voltage level can be readily set by means of a simple adjustment of the control.

Selection of right location and size of distribution regulator assures effective voltage control for present and future.

HE MODERN DISTRIBUTION-TYPE REGULATOR is a relatively new tool for the distribution engineer. While the operation of this regulator is the same as the well-known power or station regulator, the method of application may be different.

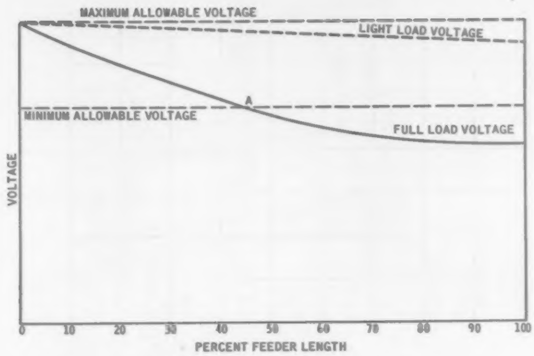
The station regulator, as the name implies, is normally installed to regulate the output voltage of a distribution substation. Since it is usually less expensive and more convenient to locate the regulator in the substation with the transformers, breakers, and other equipment, there is no problem in determining where to place the regulator. Essentially, there is no great problem in selecting the proper regulator size, since it is usually selected to match the substation transformer kva. Just when the regulators should be used depends on how much the substation voltage can be allowed to vary. The majority of substations include regulation when installed.

When it comes to regulation on the distribution system itself, the method of selecting and placing the regulator is not so obvious. The easiest method is to place the regulators at the point or points where the voltage is below acceptable limits. This can be a mistake, for as the load grows and voltage drop increases the regulator will have to be moved. If the regulator size has been determined by such a location, the regulator will be too small to be moved closer to the substation as the load increases. To overcome this, the regulator should be selected for its ultimate location rather than its immediate location.

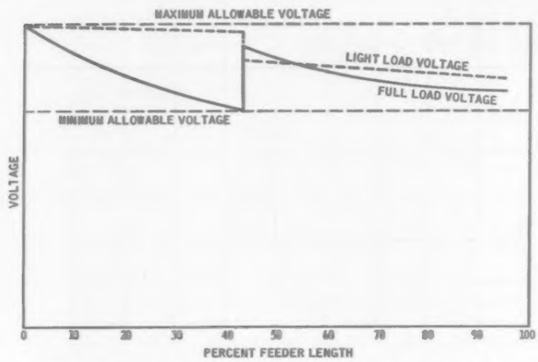
Ultimate location is determined

The best method for examining the voltage in any distribution system is to construct a voltage profile from actual voltage measurements. Measurements of maximum and minimum voltages taken at several points and plotted against feeder length give a picture of voltage conditions on the entire feeder. A typical profile for a feeder with uniformly distributed load is shown in Figure 1. Maximum and minimum allowable voltage lines have been added, indicating that the voltage at point *A* and beyond is too low. A regulator installed at this point gives a voltage profile as in Figure 2. Such a profile is satisfactory, but an increase in load gives the profile of Figure 3, indicating low voltage preceding the regulator. To prevent this, the regulator should be installed with future load conditions in mind.

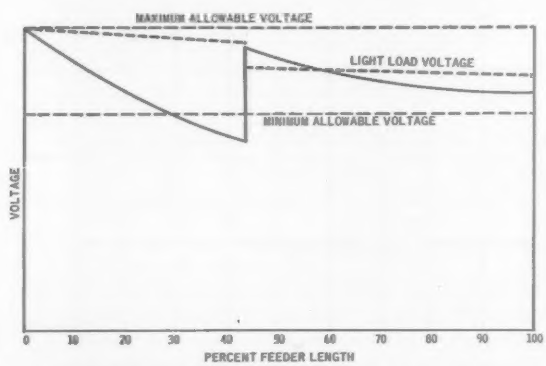
In many cases it is possible to determine future voltage profiles from existing ones. If load is uniformly distrib-



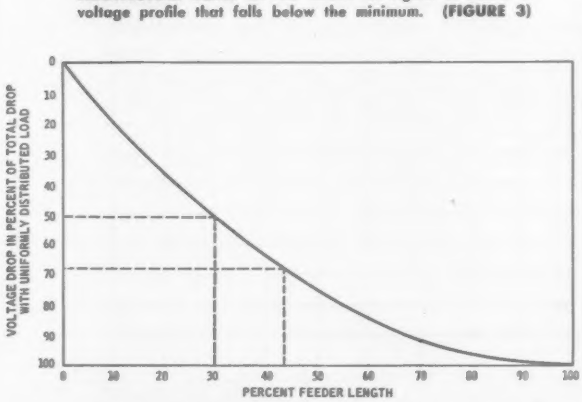
VOLTAGE PROFILE at full load, uniformly distributed, drops below minimum allowed and requires correction. **(FIGURE 1)**



PROFILE of Figure 1 is improved after regulator is added; voltage at all points is above the minimum. **(FIGURE 2)**



ADDITIONAL LOAD on the circuit of Figure 2 causes a voltage profile that falls below the minimum. **(FIGURE 3)**



CURVE OF VOLTAGE DROP may be used to determine the proper location for the distribution regulator. **(FIGURE 4)**

uted, the voltage drop at any point in percent of the total voltage drop may be expressed:

$$\text{Percent of total voltage drop} = \frac{(200 - D)\,D}{100}$$

where D is percent of total feeder length. A plot of the voltage drop for such a feeder is shown in Figure 4. It is possible to use this curve to determine the ultimate regulator location.

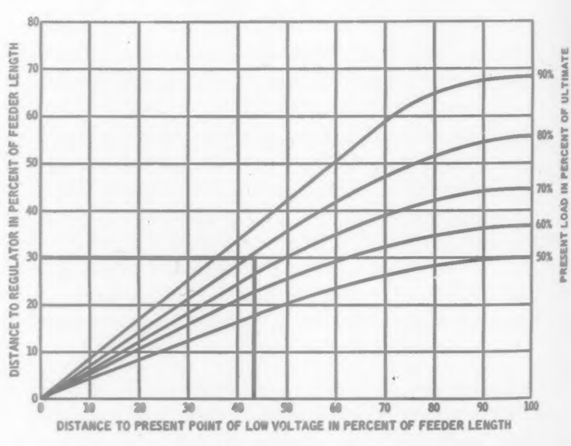
As an example, the curve of Figure 1 represents a load equal to 75 percent of the ultimate load of Figure 3. The present point of low voltage for Figure 1 is 43 percent of the feeder length, and from the curve of Figure 4 the voltage drop at this point is 68 percent of the total drop. Since the load is now only 75 percent of what it will ultimately be, the regulator should be placed where the voltage drop is 75 percent of 68 percent or 51 percent. Referring again to Figure 4, this would be at the 30 percent point. The same solution may be obtained from the curves of Figure 5, which have been prepared from Figure 4. Note that the low voltage does occur at the 30 percent point in the voltage profile of Figure 3.

In more heavily loaded areas, distribution feeders often have uniformly increasing loads. This is often the situation in urban areas where the distribution system is as shown in Figure 6. The voltage drop on such feeders may be expressed:

$$\text{Percent of total voltage drop} = \frac{D}{2}\;\frac{(30{,}000 - D^2)}{10{,}000}$$

where D is percent of total feeder length.

A plot of the voltage drop in percent of total drop for this type of distribution feeder is shown in Figure 7. Ultimate regulator locations may be determined by using this curve and the method previously outlined, or the



SAME RESULTS are obtained when curves are generalized and plotted for various uniformly distributed loads. **(FIG. 5)**

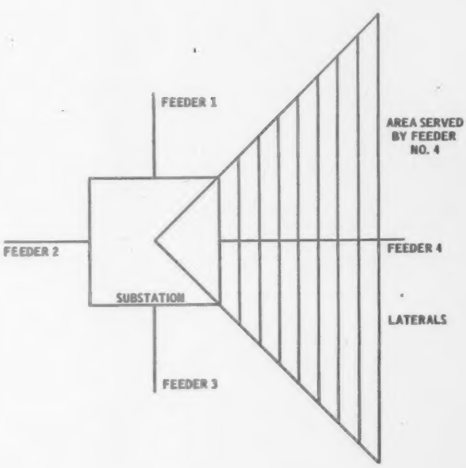
curves of Figure 8. In addition, allowance must be made for the voltage drop on the laterals immediately preceding the regulator. The exact amount of voltage drop will depend upon the number of laterals per feeder and the conductor used. In any case, it can be taken care of by installing the regulator closer to the feeder source.

Although many distribution feeders will not fall into one of the simple categories discussed above, a voltage profile is always the best way to begin when analyzing a feeder. By modifying the profile to include future loads, the ultimate regulator location may be selected.

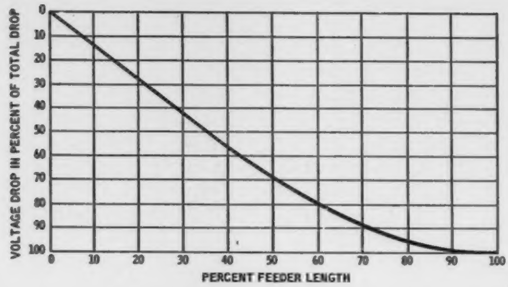
Regulator size is determined

Regulator size should be determined on the basis of ultimate feeder load. In cases of uniformly distributed loads the regulator size can be determined from the regulator location by the straight-line relationship of Figure 9. For feeders with increasingly uniform load, the regulator size can be obtained from the curve of Figure 10. In other configurations, the regulator size may be found by determining the ultimate current at the point of regulator application.

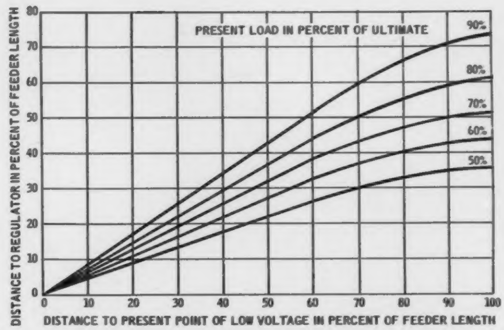
As a general rule, distribution regulators could be installed at about the 30 percent point on the feeder, or slightly less if there are laterals involved. This would take care of feeders which had low voltage at any point from 30 percent to 100 percent of their length. The only drawback to this is that installing a regulator closer to the source than necessary increases the required current rating. Selecting the regulator location with care insures using the minimum size regulator necessary for good voltage regulation.



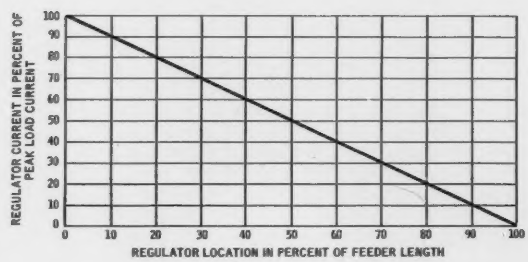
UNIFORMLY INCREASING LOAD as shown in distribution diagram is frequently found in dense load areas. **(FIG. 6)**



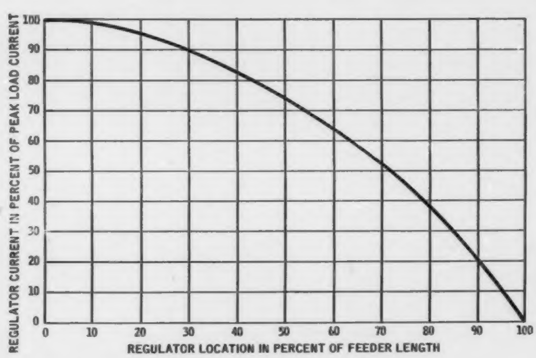
CURVE OF VOLTAGE DROP may be used to determine the regulator location for the system in Figure 6. **(FIGURE 7)**



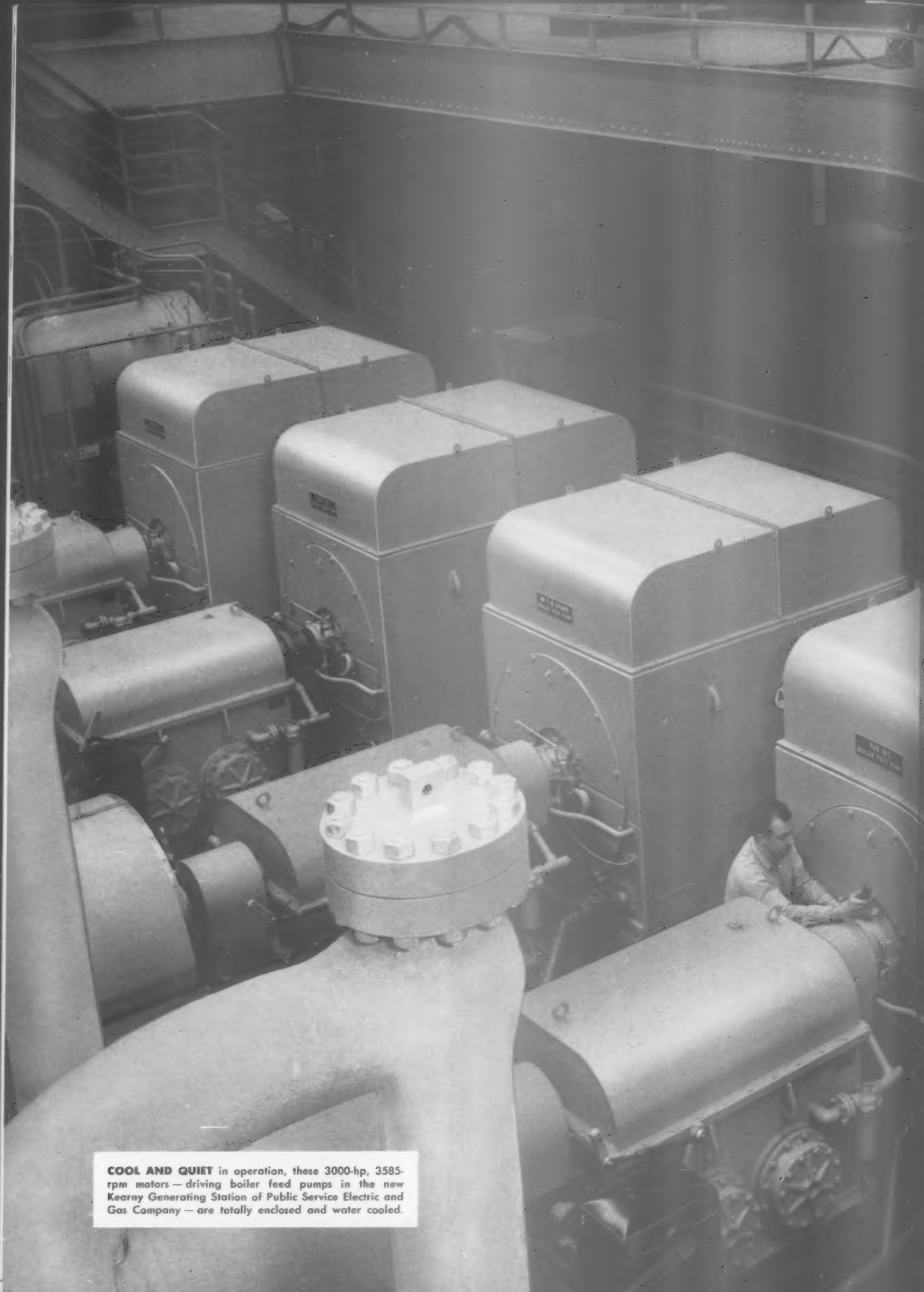
ANOTHER METHOD for finding regulator location in the system shown in Figure 6 is by means of these curves. **(FIG. 8)**



REGULATOR SIZE on feeders with uniformly distributed load is determined from straight-line function. **(FIGURE 9)**

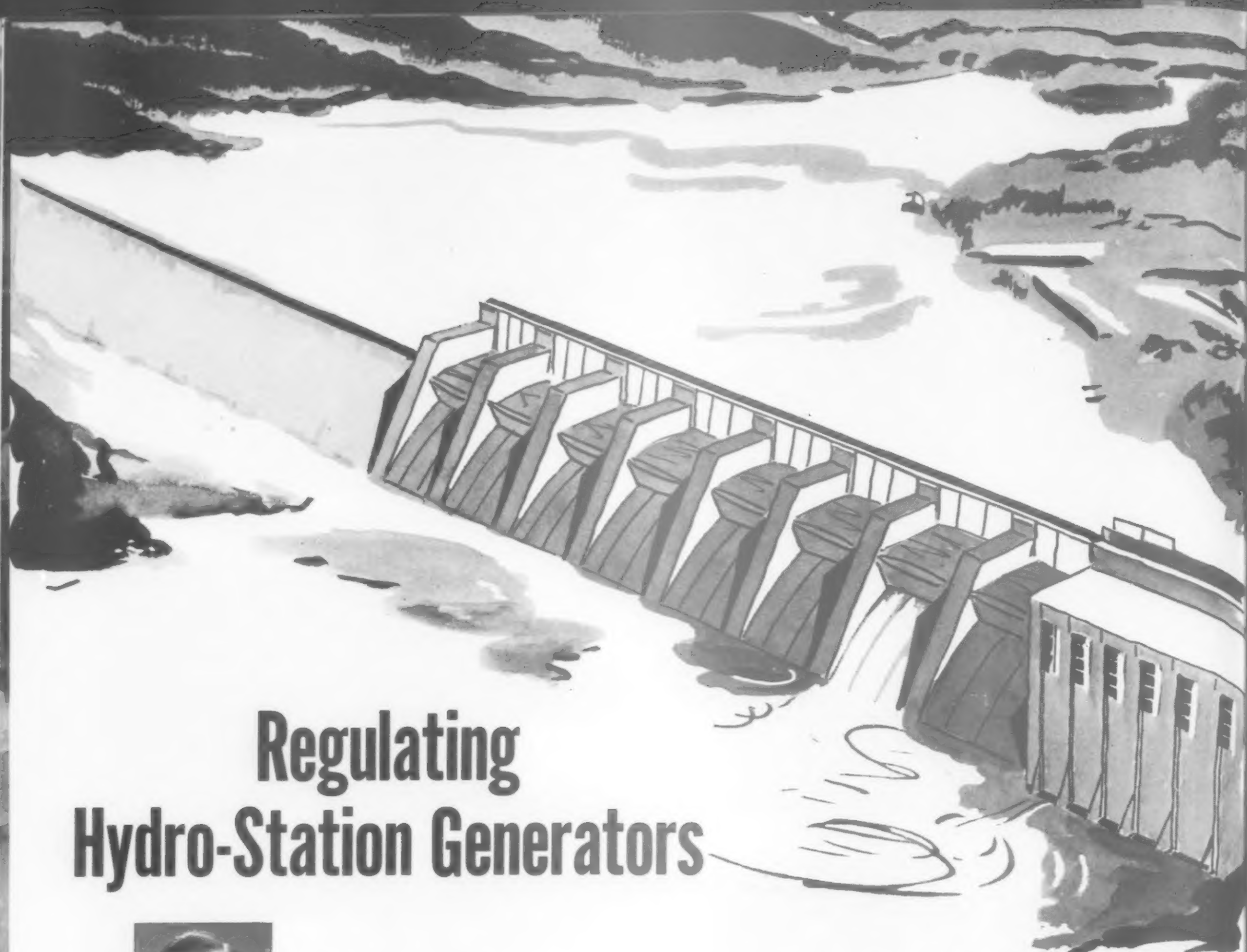


REGULATOR SIZE on feeders with uniformly increasing load is determined from curved function. **(FIGURE 10)**



COOL AND QUIET in operation, these 3000-hp, 3585-rpm motors — driving boiler feed pumps in the new Kearny Generating Station of Public Service Electric and Gas Company — are totally enclosed and water cooled.


Nº 82
BOILER FEED PUMP



Regulating Hydro-Station Generators

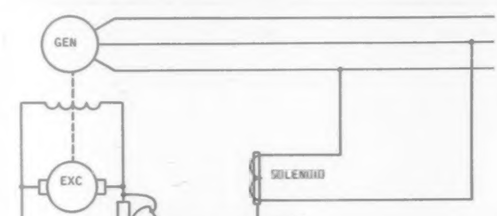
by **R. A. GERG**
Electrical Control Section
Allis-Chalmers Mfg. Co.

Wide acceptance of modern automatic hydrogenerator regulating systems is the result of proven flexibility and reliability.

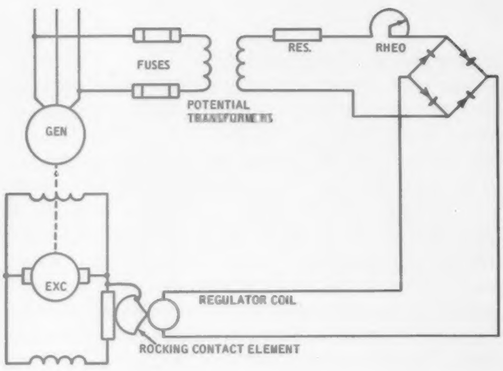
N THE MAJORITY OF AMERICAN HOMES today accurate power supply frequencies are taken for granted. In fact, modern life can be said to be geared to the electric clock fed by these power sources. However, there are still many power sources where frequency is not held constant and where regulation of voltage is not based on a constant frequency.

Hydraulic turbine-driven generators are the most common sources of large variable-frequency power. Under normal conditions the frequency of a hydrogenerator is maintained with the same accurate control as steam turbine generator frequency. However, under abnormal load conditions the frequency of these machines may vary considerably with heavy load changes. Upon sudden removal of a large block of load, with the generator isolated from the line by a circuit opening, speed may rise as high as 300 percent of normal.

The rate at which the governor is able to change the flow of water to the turbine is the chief cause of turbine speed fluctuations. Generally, such factors as the mechanical strength of the penstock determine the rate of governor change. In some installations low water conditions and heavy loads cause the frequency to drop as much as 25 percent for sustained periods of time. A similar condition is encountered on small isolated power sources subject to abnormal peak power demands.



DIRECT-ACTING REGULATOR directly controls the field excitation of generator or exciter without interposing devices. **(FIGURE 1)**



RECTIFIED MEASURE of ac voltage provides frequency insensitive control of the *Rocking Contact* regulator. **(FIGURE 2)**

Regulators can be frequency compensated

While in some variable-frequency systems the voltage regulator is designed to regulate voltage proportional to frequency, in the majority of cases the regulator is designed to keep the voltage at a constant value irrespective of frequency. There are three basic types of regulators in the latter class: direct-acting rheostatic type, indirect-acting or voltmeter type, and a static type. At present, direct-acting rheostatic regulators are used to control the majority of small generator units. A regulator of this type is shown in Figure 1.

There is no problem in making rheostatic regulators insensitive to a wide range of frequency. Generally, these units are made insensitive to frequency variations through the use of a direct current operator. The dc is supplied as a rectified ac voltage to the operating coil, as shown in Figure 2.

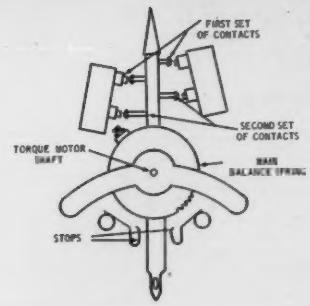
Ac torque-motor type regulators are made insensitive to frequency variations with a network consisting of capacitors and resistors designed to minimize the frequency effect of the inductive windings of the torque motor.

Indirect-acting or contact-making voltmeter-type regulators may have either a direct current or alternating current torque motor and are frequency compensated in the same manner. The contact arrangement for a torque-motor operated, indirect-acting regulator is shown in Figure 3.

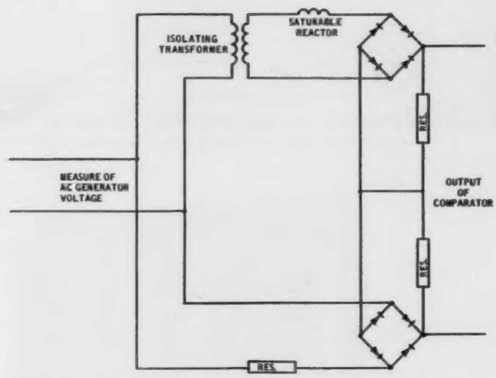
As a rule, this type of regulator has four contacts. One of the first two contacts lowers the voltage and the other raises the voltage by operating a motor-driven rheostat in the main exciter field circuit, thus raising or lowering the generator voltage as indicated by the contact-making element. However, with a sudden large change in voltage a contact of the second set of contacts is made on a 2 to 5 percent deviation voltage. These contacts operate high speed contactors which shunt a large block of resistance to apply maximum forcing voltage if the voltage is low. If the voltage is too high, a large block of resistance is inserted to reduce excitation to the generator.

Static amplifiers are versatile

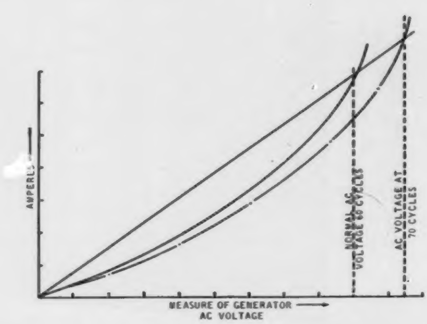
Static-type regulators are normally frequency sensitive, and many types cause a deviation in the percent regulator volt-



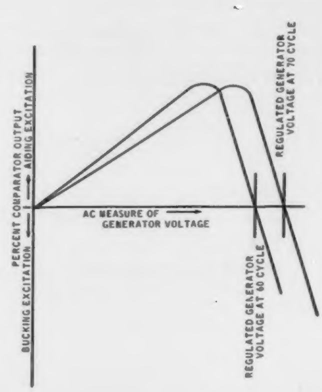
INDIRECT-ACTING regulator depends on the same method of frequency compensation as the direct-acting regulators. **(FIG. 3)**



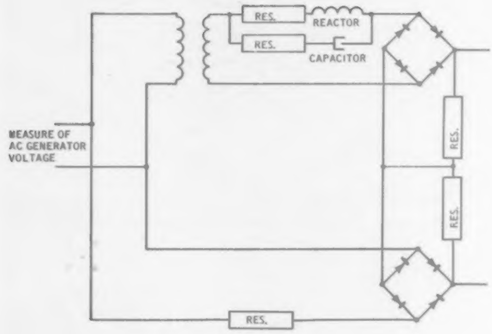
SATURABLE REACTOR in combination with a resistor is often applied in regulator circuits as a comparator. **(FIGURE 4)**



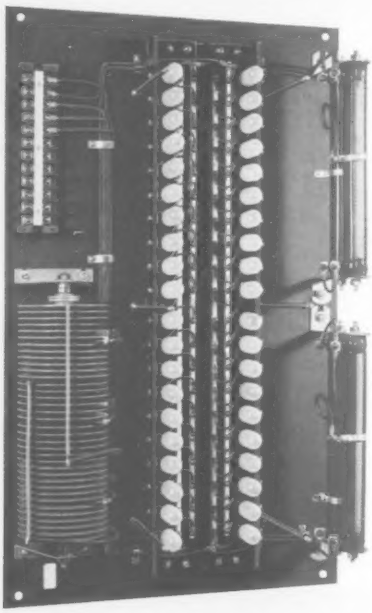
INTERSECTION of nonlinear reactor voltage and linear resistor voltage is used as the point of reference. **(FIGURE 5)**



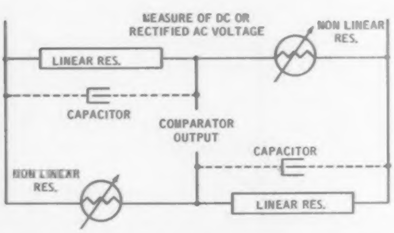
ZERO OUTPUT shifts with a change in frequence. **(FIGURE 6)**



RESISTORS AND CAPACITOR may be used for frequency compensation but result in a low gain circuit. **(FIGURE 7)**



NONLINEAR resistor elements are vacuum sealed in glass envelopes. **(FIGURE 8)**



LINEAR AND NONLINEAR resistor voltages are compared in a simple bridge circuit. **(FIGURE 9)**

age greater than the percent frequency change. Therefore, static regulators require special design considerations to obtain a suitable circuit for power equipment subject to variable frequency.

There are many circuit arrangements used in static regulators to obtain a reliable frequency-insensitive reference. This reference corresponds to the spring in a mechanical regulator. A measure of the voltage to be regulated is then compared to the reference voltage of the static network. This network is often called a comparator. In a mechanical regulator this measure of voltage is applied to a solenoid or torque motor. When the pull of the solenoid opposing a spring equals the pull of the spring, the generator voltage is at the desired value. In a static regulator the reference and measure of voltage are referred to as a comparator. When these two voltages are equal, the regulator is in balance.

The best-known references used in comparator circuits are constant voltage transformers. Some of these, however, are very sensitive to frequency and may display other undesirable characteristics if frequency compensated.

Another comparator, often applied, is a saturating reactor and a resistor, such as shown in Figure 4. Figure 5 illustrates how the nonlinear characteristic of the saturating reactor intersects with the linear characteristic of the resistor. The resulting reversible voltage balances the circuit, as shown in Figure 6. The output of this circuit in one polarity will increase generator voltage, while the output of the circuit in the other polarity will reduce voltage. The zero output shifts with frequency and thus alters the regulated voltage. The circuit may be compensated to reduce this frequency variation. A modified circuit of this type is shown in Figure 7. This particular circuit results in a low gain circuit and therefore is seldom employed.

A series-connected saturable reactor that is saturated by a built-in permanent magnet is another type of frequency reference source. This unit has almost rectangular-shaped output current, and within certain limits is nearly independent of line voltage, frequency, and burden. This type of reference may be used for direct current as well as alternating current systems. An auxiliary source of alternating current is required when this device is employed in a direct current system. While there are many other devices used as references in frequency-insensitive circuits, those described represent some of the more practical and less complicated devices.

Nonlinear compensators used

One of the most practical and versatile comparators is a nonlinear bridge, shown in Figure 8. This element, consisting of a filament in a vacuum, will operate equally well on a direct current or a rectified alternating current and requires no auxiliary power. Figure 9 shows a bridge of this type. The output characteristic of the circuit when variable voltages are applied to its input terminals is similar to Figure 6 except its output remains constant regardless of frequency. The variable-resistance element used in this circuit was carefully selected for its reliability. Since hydrogenerator units may be located in an unattended station which is operated only by remote supervisory control, reliable performance for long periods of time under

all types of conditions is a prerequisite for the generator control. The equipment must also operate accurately under a wide range of ambient temperatures.

In a circuit recently adopted for hydrogenerator regulators, 20 nonlinear resistance elements are connected in parallel for each side of the bridge. The life expectancy of this type of nonlinear resistance element is shown in Figure 10. This illustration contains three life expectancy curves. The nonlinear resistance element employed in this bridge is operated at about 50 percent rated voltage. At this voltage and without vibration the resistance element would have an expected life of many thousand years. The same element subjected continuously to severe vibration would be expected to last about 60 years. However, the magnitude of vibration used for this curve is far more severe than ever would be encountered in any hydro application; therefore normal life expectancy is many times 60 years.

Reliability is assured

The nonlinear bridge used in this type of application uses 20 parallel elements on each side of the bridge. Thus the failure of one element will result in not more than a 5 percent change in regulated voltage. This small voltage deviation can be corrected with the volts-adjust autotransformer without removing the regulator from service. On a scheduled shutdown this element can then be replaced, or a like unit can be removed from the other side of the bridge. It is possible to remove up to 10 elements from each side of the bridge and still obtain satisfactory operation.

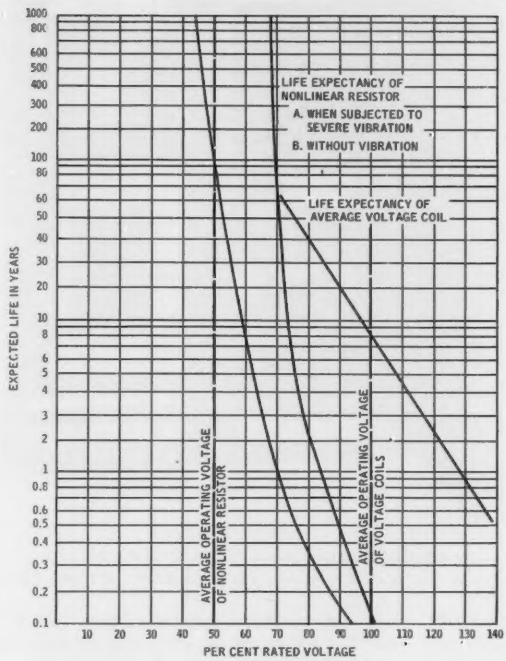
With the minimum life expectancy of this type of nonlinear bridge established at 60 years, distribution curves indicate that not more than one out of 40 elements will fail during 20 years of operation, that at least 35 will be in operation after 40 years, and that 20 elements will be functioning after 60 years. Therefore, without replacing a single element, a bridge with 10 parallel nonlinear elements would be expected to be in operation even after 60 years of service. Special care in inspection and testing are taken to insure this performance.

The third curve represents the life expectancy of some common types of electrical coil insulation in relation to the percent voltage applied to the device in which it is used. According to this curve, 7 years is the normal life expectancy. However, most manufacturers will use a voltage figure less than 100 percent shown in this curve and obtain an expected life of considerably more than 7 years. These curves show that the nonlinear resistance elements will outlast the other equipment used in such circuits.

The type of nonlinear element in the unit shown in Figure 8 is for all practical purposes independent of the wide range of ambient temperatures encountered in any hydro installations. This is the result of selecting linear resistor elements with temperature coefficients matching the characteristic of the nonlinear resistance element as its normal operating temperature.

Time constant important

Since the operating temperature of the nonlinear resistance elements changes with each change of voltage, this type of



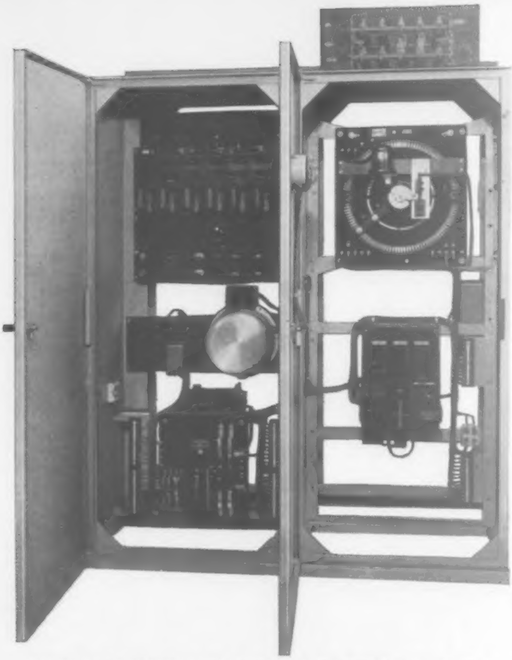
LIFE EXPECTANCY of these nonlinear resistance elements is far longer than normal equipment life. **(FIGURE 10)**

bridge has a thermal time constant. That is, after each change in applied voltage, a short period of time is required for the output of the bridge to reach a steady-state condition. The time constant is reduced to an insignificant value by the selection of the correct nonlinear elements. A typical thermal time constant of such a bridge might be .04 of a second; for all practical consideration, the time constant may be disregarded when two capacitors are added, as shown in Figure 9. These capacitors are used only on special applications, since the inherently short time constant of the nonlinear bridge is not generally a disadvantage.

The nonlinear bridge voltage comparator and other static elements as well as a rotary-amplifier *Regulex* generator, are shown in the block diagram in Figure 12 and in the simplified schematic in Figure 13.

The system is placed in or out of operation in a very simple manner. This sequence of operation is comparable to the operation of the comparison circuit used in constant frequency circuits.[1] To place in operation, the generator is brought up to rated voltage by manual control identical to that of any generator having a self-excited exciter. With the generator at rated voltage, the manual-automatic control switch is turned to the test position. The regulator volts-adjust variable autotransformer is then turned to a position corresponding to zero output of the rotary amplifier. Now, the control switch may be turned to the automatic position, transferring the generator control to the

[1] "Five Stages to Stability," H. D. Timm and T. B. Montgomery, Allis-Chalmers *Electrical Review*, Third Quarter, 1951.



STATIC COMPONENTS of *Regulex* rotary amplifier type regulator are mounted in a small auxiliary cabinet. **(FIGURE 11)**

regulator. With this sequence the transfer from manual to automatic control is accomplished without generator output disturbance either when the generator is loaded or unloaded. The procedure for transfer of the generator from automatic to manual control can be accomplished just as easily. To change to manual control, the exciter field rheostat is adjusted so that rotary amplifier output is zero, and then the control switch is turned to the manual position.

The operation of the regulator under automatic operation is as follows: A three-phase voltage is obtained from a potential transformer connected to the generator bus. This three-phase voltage is then rectified by a three-phase full-wave rectifier and applied to the input terminals of the nonlinear comparator. The output of this comparator will be zero if the generator voltage is at the value determined by the setting of the volts-adjust variable autotransformer. If the voltage is lower than desired, the output of the bridge will cause an increase in the excitation to the generator. With a voltage higher than desired, the output of the comparator will reverse and cause a reduction of excitation to the generator.

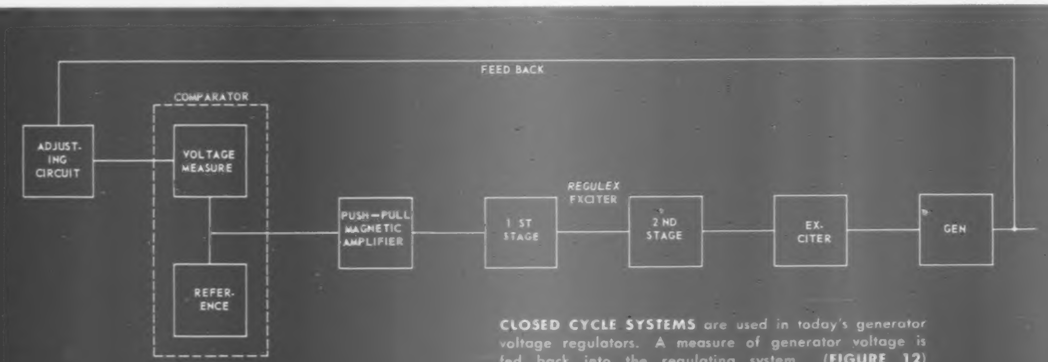
The output of the comparator is greatly amplified by the push-pull, self-saturating magnetic amplifiers. These units, operated in push-pull, are practically insensitive to frequency, since a change in frequency changes both elements in the same direction and thus cancels out.

The output of each amplifier is fed to an isolated field winding in the first stage of the two-stage rotary amplifiers. Since the resultant excitation supplied by these two amplifiers reverses, the rotary amplifier reverses also. Due to its high amplification, the rotary unit can regulate the generator voltage within the narrow limits required by modern systems. The output of the rotary amplifier may either add to or subtract from the normal excitation of the exciter.

Minimum excitation accurately controlled

The ability of this system to limit voltage rise on instantaneous loss of load, limit voltage dip under fault conditions, and return voltages to normal values is unequaled by its many predecessors. This type of static circuit, having no mechanical parts to accelerate and decelerate, starts corrective action the instant voltage deviates from normal. Since all of the elements in this circuit have extremely short time constants, the corrective voltage of the rotary regulator is quickly applied to the exciter field.

This ability to start corrective action the instant voltage deviates from normal is a very important feature when load is suddenly removed from the terminals of a hydrogenerator. Upon full load rejection the speed may increase from 130 to 300 percent normal values. Despite the fact that overspeeds up to 150 percent are common in the average installation, the regulator must attempt to keep the generator voltage within narrow limits of rated value. If speeds over 150 percent of normal are encountered, it is common practice to open the generator exciter field breaker and disconnect from the line equipment which would be damaged by this frequency. On installations where it is not practical to remove the equipment from the line, the equipment must either be designed to handle these frequencies or have its power supplied from an auxiliary



CLOSED CYCLE SYSTEMS are used in today's generator voltage regulators. A measure of generator voltage is fed back into the regulating system. **(FIGURE 12)**

power source. In either case, the regulating system will regulate generator voltage within narrow limits at sustained overspeeds beyond 300 percent of normal as well as for underspeeds as low as 75 percent of normal. The arrangement is shown in Figures 12 and 13.

The basic voltage regulator is designed to operate with a number of accessories, such as a reactive current compensator, line-drop compensator, automatic minimum excitation limiter, and maximum current limiter for condenser operation.

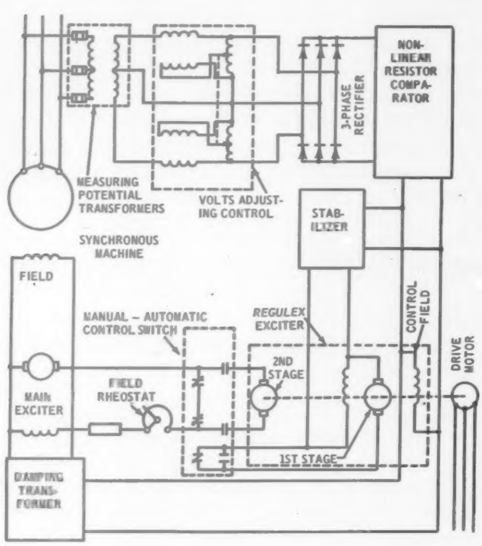
Reactive current and line-drop compensators are basically the same elements as used for similar regulating systems in constant frequency circuits.[2] However, special design considerations are required so that the elements will not be affected by frequency changes.

An automatic minimum excitation limiter is often required in hydrogenerator regulating systems because of line charging and similar conditions. The unit is similar to those employed in other types of static regulators,[3] except that special design considerations must be given for its operation during underspeed and overspeed. Maximum current limiter design is also affected by these operating conditions.

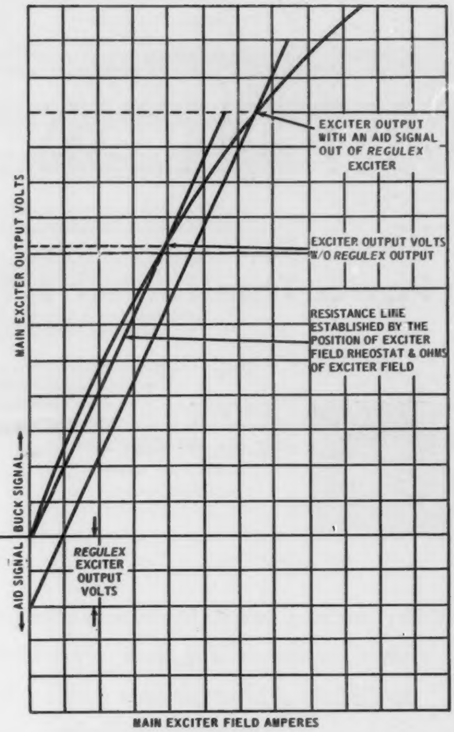
Regulating systems combining rotary amplifying elements with combinations of static circuits provide a greater flexibility of control for modern hydrogenerators. These systems now make possible a greater degree of automation by providing such features as automatic minimum excitation control, rapid response on line disturbances, and reliability.

[2] "Rotating Regulators Control Systems Reactive Current," H. D. Timm and T. B. Montgomery, Allis-Chalmers *Electrical Review*, Fourth Quarter, 1951.

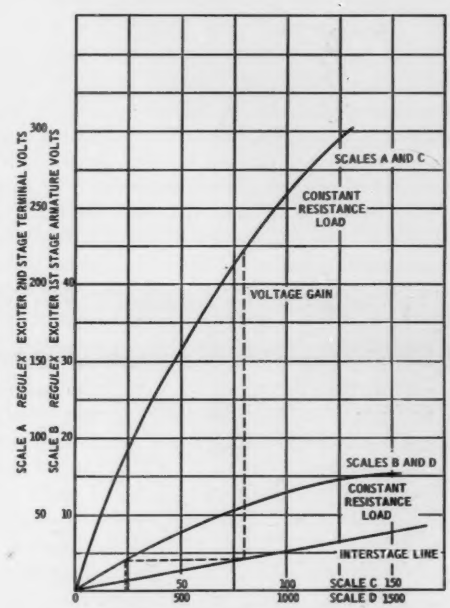
[3] "Pull-Out Reserve — Controlled and Indicated," T. B. Montgomery and D. V. Hotson, Allis-Chalmers *Electrical Review*, First Quarter, 1952.



BASIC REGULATOR SCHEME has the features needed for frequency insensitive control of modern hydrogenerator. **(FIG. 13)**



SMALL AID SIGNAL from the *Regulex* exciter results in a big boost in main exciter output. **(FIGURE 14)**

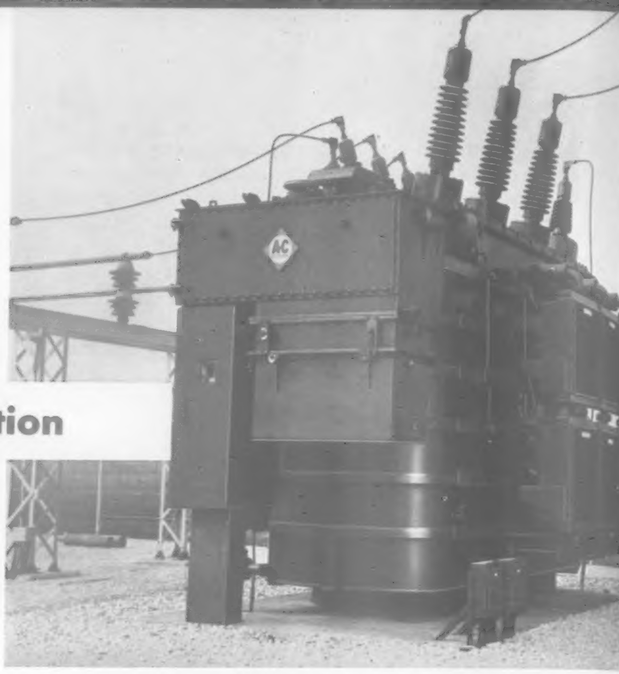


HIGH VOLTAGE GAIN makes the *Regulex* exciter especially adaptable for voltage regulator applications where field forcing is required to obtain a quick restoration of generator voltage after disturbance. **(FIG. 15)**

COST ANALYSIS

In Power Transformer Selection

by **L. W. SCHOENIG**
Transformer Section
Allis-Chalmers Mfg. Co.



FORCED OIL/FORCED AIR-cooled (FOA) transformers are lighter, smaller, and lower in cost per kva than are the transformers with natural oil and air circulation. The unit shown is rated 50,000 kva, three-phase, HV 132 kv, LV 72.45 kv.

Many factors must be considered in the amortization of a power transformer to obtain a true picture of its cost.

STRETCHING YOUR TRANSFORMER DOLLAR starts with the decision whether to use three-phase or single-phase units. This decision is not a simple one and must be based on a number of factors, such as the reliability of transformers, the risk of service interruption that can be taken, and the influence of station design. If transformers are being selected for an existing station, the station design and construction may preclude the use of single-phase or three-phase transformers. In an existing station where the structure has been specifically laid out for single-phase transformers, it may not be physically or economically practical to use a three-phase unit. Conversely, it may be impractical to use a single-phase transformer in a station which had been designed for three-phase units.

The necessity for a decision between single-phase and three-phase transformers is relatively new. Early transformers were invariably single-phase. Single-phase transformers were used to obtain the best possible continuity of service, since transformer failures 25 or 30 years ago were not uncommon. The use of single-phase transformers was a desirable method of handling the situation. It was general practice to have a spare single-phase unit in each substation and to have all transformers equipped with wheels so the spare would be readily available. The use of single-phase transformers was an economical method of obtaining continuity of service.

Three-phase units in greater demand

The insulating materials, design tools, and "know-how" which were available in the early days of transformer construction left much to be desired. The oscilloscope, impulse generator, modern insulating material, better quality insulating oil, lightning arresters, and relay systems are all of relatively recent vintage. Each has contributed to the reliability of present-day transformers, and collectively they have made transformer failures almost a thing of the past. In view of the excellent service record of recent transformers, the trend today is toward the use of three-phase units. Transformers which were beyond comprehension a few years ago are now being built as three-phase units. Transformers of 150,000 kva are rapidly becoming run-of-the-mill units. Ratings of 175,000, 220,000, and 300,000 kva are also being constructed.

One of the principal reasons why three-phase power transformers predominate today is the saving in initial cost. This cost is approximately 95 percent of three single-phase units, or 72 percent of four single-phase units. Also, three-phase units are advantageous in that they require much less substation space, lower foundation cost, and perhaps a much simpler station layout.

The basic insulation level of transformers for many applications can be reduced if proper protection is provided. The use of reduced insulation is usually considered for transformer windings of 115 kv and higher which are wye connected and solidly grounded. Voltage surges due to impulse or switching can be limited to materially lower magnitudes on solidly grounded systems than on un-

grounded systems. The use of 115-kv class insulation on 138-kv transformer windings and 196-kv or 180-kv on 230-kv windings is commonly accepted practice.

Reduced insulation results in lower initial costs and impedance losses, and less weight and floor area.

Cost depends on cooling method

Transformers for most applications will be one of four types. These transformers, with a brief description of each type in the order of descending initial cost, are:

(1) Oil-immersed and cooled by natural air circulation, Type OA has fin-type radiators to increase the radiating surface.

(2) Type OA/FA, which is like the OA except that it has an increased rating, of from 15 to 33½ percent, obtained by the addition of forced-air fans.

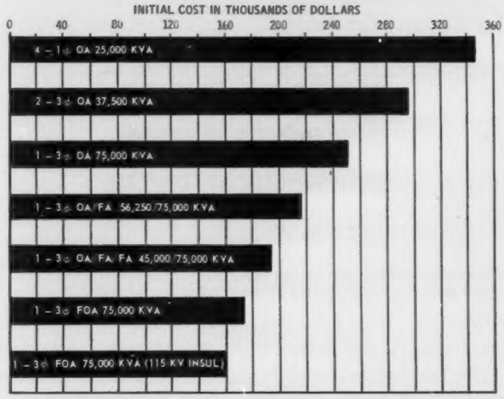
(3) Type OA/FA/FA, which is similar to Type OA/FA except that the self-cooled rating is increased 67 percent in two steps by two groups of forced-air fans.

(4) Type FOA transformer uses pumps to circulate oil through external oil-to-air heat exchangers.

The latter type transformer has no self-cooled rating as such; however, it will carry full load for a short time without its cooling equipment in operation.

The effect of cooling on transformer characteristics is shown in Table I. Each of the transformers is a 138-kv, three-phase unit and has a top rating of 75,000 kva. It can be seen that the self-cooled unit has the highest core loss, exciting current, weight, and the lowest total loss and impedance. The self-cooled/forced air/forced air-cooled unit has the lowest core loss and exciting current and the highest impedance.

Transformers with forced cooling can be applied to power systems at a considerably lower dollar cost per kva than self-cooled units. Figure 1 compares the initial cost of the various methods of handling a 75,000-kva, 138-kv load. The initial cost of four 25,000-kva, single-phase, Type OA transformers was included for comparison purposes. If all factors other than initial cost are neglected, either Type FOW transformers, where cooling water is available, or FOA transformers, where adequate supply of cooling water is not available, would be applied to all systems. Since other factors must be considered, the solution is not so simple.



RELATIVE COST of various combinations of transformers is shown. These are initial costs only. **(FIGURE 1)**

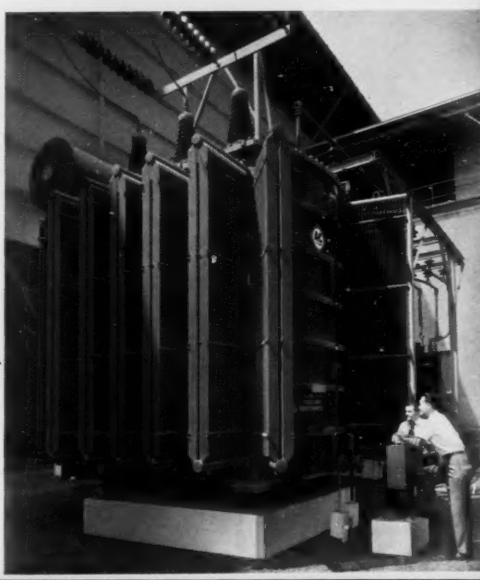
As indicated in Table I, the characteristics of transformers are influenced by cooling. Figure 2 graphically compares transformer losses for various methods of handling a 75,000-kva, 138-kv load. Core loss, total loss, and power for cooling in the case of forced-cooled units have been indicated. If transformer losses were the criterion, all transformers would be three-phase, self-cooled units. Figure 3 compares the efficiency of Type OA and FOA, 75,000-kva, 138-kv, three-phase transformers. The self-cooled unit is sometimes referred to as a high efficiency transformer, and the forced oil-cooled unit as a low efficiency transformer. These designations are somewhat misleading, as the efficiency of both types is very high. The transformer, regardless of the cooling method, is one of the most efficient pieces of major equipment in the power system.

As indicated, the initial cost of a forced-cooled transformer is considerably less than a self-cooled unit but the

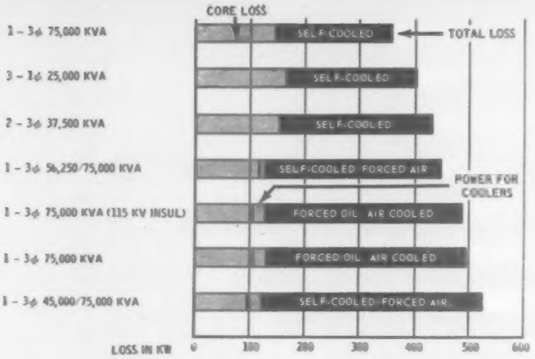
TABLE I

	OA	OA/FA	OA/FA/FA	FOA	FOA*
Rating, kva	75,000	56,250/75,000	45,000//75,000	75,000	75,000
Impedance, %	8	8/10.7	8/13.3	12	11.5
Exciting current, amp	2.3	1.85	1.55	1.73	1.71
Core loss, kw	143	116	97	108	107
Total loss, kw	357	424	500	470	463
Power for cooling, kw	...	8	25	23.5	23
Weight, lb.	360,000	310,000	285,000	260,000	230,000

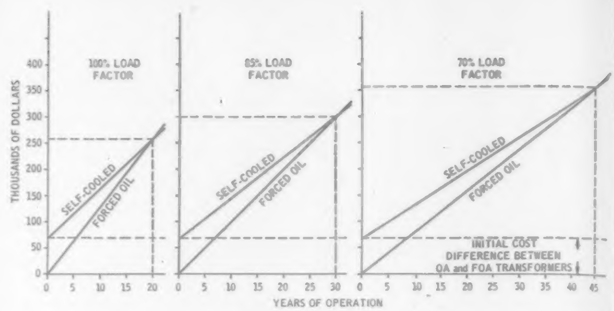
* Reduced insulation on HV winding.



NATURAL CIRCULATION cools this 30,000-kva, 69—13.8-kv, three-phase transformer. No power is required for cooling.



COOLING LOSSES are shown for various types and sizes of transformers. Cooling cost must be included. **(FIGURE 2)**



SELF-COOLED TRANSFORMERS eventually cost less per kva than forced oil-cooled transformers. **(FIGURE 4)**

losses considerably more. The saving in initial cost is offset by the higher losses. There are many ways of determining the cost of losses. The cost will no doubt be different for various systems and will vary with parts of a given system. The energy charge for transformer losses has been figured at 2.5 to 7 mils per kwhr.

If losses are to be considered, the simplest method of determining overall cost of a transformer installation is to capitalize the losses, consider the initial cost, and neglect all other factors. This method is based on the premise that it is unnecessary to increase generating capacity to supply transformer losses, and neglects completely the cost of financing the transformer investment. However, load factor has a definite bearing on the total transformer losses, and since this affects the capitalization it should be considered. This type of comparison is shown in Figure 4, which compares forced oil air-cooled and self-cooled three-phase transformers. Losses were evaluated at 3 mils per kwhr for 100, 85, and 70 percent load factor. The initial cost figures from Table I and losses from Table II were used in determining these charts. The charts indicate that, at 100 percent load factor, 20 years are required for the cost of the higher losses of the forced oil-cooled transformer to overcome the higher initial cost of the self-cooled transformer. At 85 and 70 percent load factors, the time required is 30 and 45 years, respectively.

Figure 5 shows the effect of an energy cost of 5 mils instead of 3. When capitalized at 5 mils, the higher losses of the forced oil-cooled transformer overcome its initial cost advantage in 12, 17.5, and 27.5 years, respectively, for 100, 85, and 70 percent load factors.

When excess generating capacity is not available to supply losses, or when a more thorough comparative analysis of the cost of transformer installations is needed, these items must be taken into consideration:

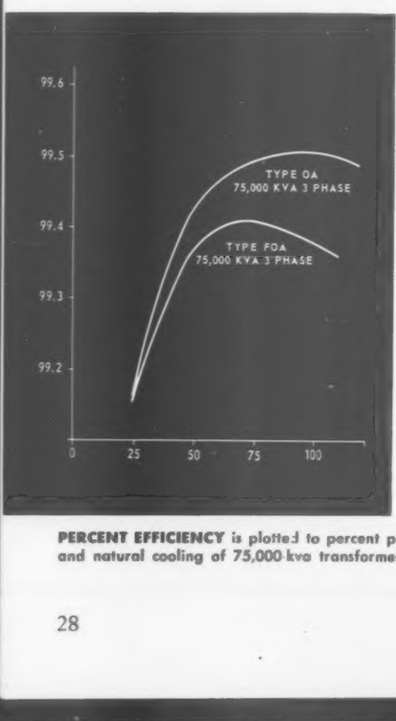
1. Cost of installing additional generating equipment.
2. Interest on money required to finance initial transformer cost.
3. Interest on money required to finance cost of additional generating equipment.
4. Insurance.
5. Depreciation.
6. Taxes.

There are many ways of considering these items. One

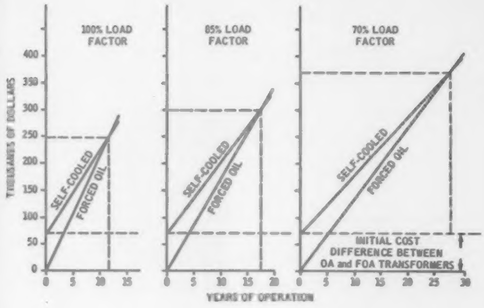
TABLE II

	OA	OA/FA	OA/FA/FA	FOA	FOA*
Rating, kva	75,000	56,250/75,000	45,000//75,000	75,000	75,000
Loading (85% load factor), kw	63,500	63,500	63,500	63,500	63,500
Impedance, %	8	9	12.75	12	11.5
Exciting current, amp	2.7	2.2	1.835	2.06	2.05
Core loss, kw	143	116	97	108	107
Load loss (63,500 kva), kw	154	223	291	262	257
Power for cooling, kw	..	8	25	23.5	23
Total loss, kw	297	347	413	393.5	387
Reactive loss, kvar	5,090	5,720	8,100	7,625	7,150
Excitation loss, kvar	1,715	1,400	1,165	1,310	1,305
Total kvar	6,805	7,120	9,265	8,935	8,455
Initial transformer cost, dollars	254,000	218,000	198,000	179,000	160,000
Transformer carrying charge at 10%	25,400	21,800	19,800	17,900	16,000
Demand charge at 10% at $175/kw	5,200	6,070	7,240	6,875	6,770
Energy cost at 3 mils/kwhr	7,800	9,100	10,850	10,320	10,170
Kvar at $7/kvar at 10%	4,765	4,985	6,485	6,255	5,920
Total annual cost at 10%	43,165	41,955	44,375	41,350	38,860

* Reduced insulation on HV winding.



PERCENT EFFICIENCY is plotted to percent power for forced and natural cooling of 75,000 kva transformer. **(FIGURE 3)**



BREAK-EVEN POINT is reached sooner when energy cost is increased, while other factors remain equal. **(FIGURE 5)**

convenient method is to convert all items to an annual charge. First cost can be represented by the carrying charge required for the investment. An approximate carrying charge in percent may be determined by the sum of the following percentages:

Interest	5
Depreciation	3
Taxes	1.5
Insurance	0.5
	10.0

The interest, insurance cost, and method of handling depreciation will differ for each system, resulting in carrying charges which vary from 7.5 to 15 percent.

Selecting a power transformer can be as simple or as complicated as one wants to make it. The more factors considered, the more complicated the problem becomes. Table II is a rather common and somewhat involved method of comparing different types of three-phase transformers. This comparison considers initial cost, demand charges for supplying losses, energy cost of losses, and reactive kva. A carrying charge of 10 percent, energy cost of 3 mils per kwhr, installed cost of generating equipment of 175 dollars per kw, and installed capacitor cost of 7 dollars per kva were used. With these values the annual cost of a Type FOA transformer would be about 5 percent less per year than a Type OA unit. Reduced insulation (550-kv basic insulation level) on the Type FOA unit results in an additional 5 percent saving in annual cost.

Energy cost and installed generating capacity costs will vary for each system and, for that matter, for each part of a given system. The comparisons in Table II, however, are typical for generating station transformers.

Table III shows the effect of higher energy cost and higher installed cost of generating equipment. An energy cost of 5 mils per kwhr and an installed cost of generating equipment of 250 dollars per kw were used, with all other factors remaining the same. The comparison now indicates that the annual charge for the self-cooled transformer would be about 1.5 percent less per year than the forced oil-cooled unit with comparable insulation. The annual charge of the Type FOA unit with reduced insulation, however, is 4 percent less than the 650-kv basic insulation level, self-cooled transformer. The annual charge for the Type OA/FA is about the same as for the Type OA unit. The comparison in Table III is typical for a substation transformer.

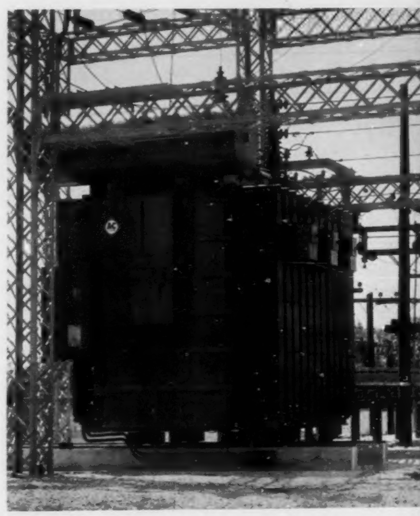
It is desirable to give more weight to the losses which must be transmitted over the transmission line than to consider the increased cost of the transmission line. The increase in cost was reflected in this case by increasing the cost of installed generating capacity.

Many factors, including insulation level, cooling, number of phases, cost of losses and accounting methods, affect the selection of power transformers. It cannot be said that one type of power transformer is the right choice for all applications. Each transformer is a problem in itself and should be selected by considering all the factors.

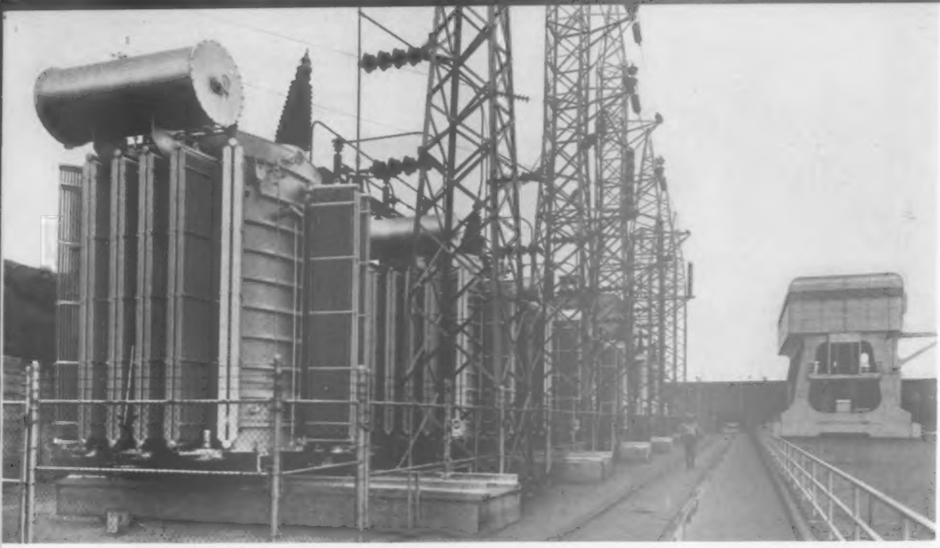
TABLE III

	OA	OA/FA	OA/FA/FA	FOA	FOA*
Rating, kw	75,000	56,250/75,000	45,000//75,000	75,000	75,000
Loading (85% load factor), kw	63,500	63,500	63,500	63,500	63,500
Impedance, %	8	9	12.75	12	11.5
Exciting current, amp	2.7	2.2	1.835	2.06	2.05
Core loss, kw	143	116	97	108	107
Load loss (63,500 kva), kw	154	223	291	262	257
Power for cooling, kw	. .	8	25	23.5	23
Total loss, kw	297	347	413	393.5	387
Reactive loss, kvar	5,090	5,720	8,100	7,625	7,150
Excitation loss, kvar	1,715	1,400	1,165	1,310	1,305
Total kvar	6,805	7,120	9,265	8,935	8,455
Initial transformer cost, dollars	254,000	218,000	198,000	179,000	160,000
Transformer carrying charge at 10%	25,400	21,800	19,800	17,900	16,000
Demand charge at 10% at $250/kw	7,425	8,675	10,320	9,825	9,675
Energy cost at 5 mils/kwhr	13,000	15,200	18,100	17,200	16,950
Kvar at $7/kvar at 10%	4,765	4,985	6,485	6,255	5,920
Total annual cost at 10%	50,590	50,660	54,705	51,180	48,545

* Reduced insulation on HV winding.



COOLING FANS increase the power ratio of this three-phase transformer from 50,000 kva to 66,667 kva.



LOCATED AT TVA's Fort Loudoun Dam, these single-phase power transformers are rated 21,000/28,000 kva.

by **R. BRUCE SHIPLEY**
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Tensors and Transformer Connections

PART I

Here's a method of eliminating transformer magnetizing currents — a necessary step when using tensors to analyze faults.*

OWER NETWORK ANALYSIS takes many forms, depending upon the particular problem and the results desired. Symmetrical components present an excellent method of numerical analysis when the circuits are symmetrical. When circuits are unsymmetrical, the solution becomes more difficult, even though Alpha, Beta, and zero components were developed to handle certain types of dissymmetry.

Tensor analysis, on the other hand, is applicable to any circuit and to any degree of dissymmetry, including dissymmetry resulting from open conductors, banks of dissimilar transformers, unsymmetrical connections, unbalanced generated voltages, and faults between systems of different voltages. Tensor analysis produces maximum simplification in the analysis of phase-to-phase and phase-to-ground faults on unsymmetrical systems that have one source of current supply.

**Editor's note:* This is a three-part article of which only the first part will appear in the Allis-Chalmers *Electrical Review*. For your convenience, the entire article has been prepared as an individual booklet and will be sent free upon request. Write the Editor, Allis-Chalmers *Electrical Review* for your copy, or send the enclosed postcard.

Part two explains a method of using fictitious single-phase currents to determine transformer connections, and part three explains how part one is used in tensor analysis to determine actual amperes flowing in the circuits.

When making the qualitative portion of the analysis, two steps are necessary: (1) Make an actual circuit diagram; (2) map out on this diagram the relative magnitudes and directions of all currents that flow in the circuit. This can usually be done by inspection — at most it requires simple arithmetic, algebra, and possibly a scant knowledge of basic symmetrical components. This portion of the analysis may be used to check and determine connections for phasing apparatus, for polarizing relays, and similar operations. Once the qualitative portion of the analysis is completed, the currents in all branches of the circuit can easily be determined by a simple routine manipulation. This manipulation requires the use of the actual circuit diagram, actual voltages, actual circuit ohms regardless of the circuit voltage, and actual transformer ohms modified by the turns ratio.

Specifically, the numerical portion follows tensor analysis as described by Gabriel Kron. The method of mapping out the relative magnitudes and directions of the currents has far greater physical significance than Kron indicates in *Tensor Analysis of Networks.*

The qualitative method explained

When single-phase currents are introduced into a three-phase system, they are transmitted and transformed as single-phase currents. On an unloaded system, normally assumed for fault analysis, these currents may be added or subtracted at the junction points in accordance with their direction. Thus an accurate portrayal of the relative current directions and magnitudes may be obtained by the use of arithmetic.

Most power system faults are either phase to phase or phase to ground. They cause single-phase currents to flow on the three-phase system. These single-phase currents may be accurately represented by a system of arrows drawn on the connection diagram.

When determining how transformers should be connected for proper phasing, it is advantageous to assign a set of fictitious single-phase currents to be traced throughout the system. Since these currents will usually never flow in the actual power circuit, their actual magnitude need not be known.

Indicating polarity of transformer windings

In this analysis the transformer is merely a coupled magnetic circuit with a constant transformation ratio and no exciting current. Associated with each winding on the magnetic core is the concept of polarity. Polarity is usually indicated on diagrams by a dot at one of the terminals on each winding. From a current standpoint this merely means that when current enters the dot on one winding of a two-winding transformer it must flow away from the dot on the other winding. In this analysis each terminal of every coil is to be numbered. One terminal is labeled 1 and the other terminal 2. When current enters terminal 1 and leaves terminal 2 it is considered positive. The other direction is negative. Thus, on a two-winding transformer, if current enters terminal 1 on one winding it must leave terminal 1 on the other winding. In a multi-winding transformer the magnetic circuit must balance. The current must be reversed on at least one winding to make the total magnetic flux produced by all windings equal to zero.

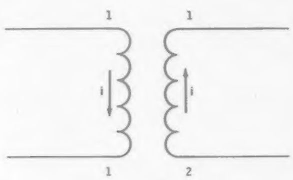


FIGURE 1

In Figure 1 the two-winding transformer is represented by two parallel windings. If the transformer ratio is 1:1, the currents in the two windings must be equal in magnitude and one current is reversed in direction; or as stated before, when the current enters the polarity mark on one side, it must leave the same polarity mark on the other side. If the transformer has some ratio other than one, the magnitude of the current is changed by that ratio as it passes through the transformer.

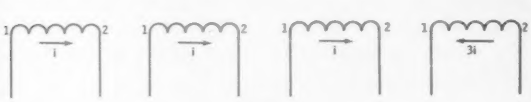


FIGURE 2

The multi-winding transformer is represented by as many parallel windings as there are windings on the individual magnetic core. A four-winding transformer with the same number of turns on each winding is illustrated graphically in Figure 2.

If three equal currents flow into the number 1 terminals of the first three windings, then their sum must flow in the opposite direction in the fourth winding. If the ratio of turns is modified, then the magnitude of the currents must be modified to maintain the magnetic balance. When the currents are all single-phase and are in phase, this modification may be performed arithmetically.

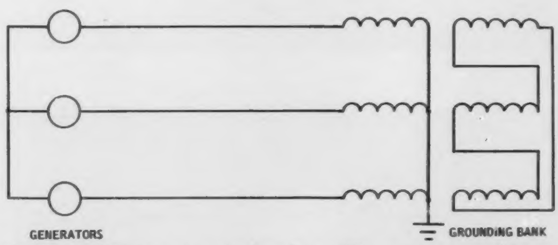
Transformer interconnection affects analysis

The methods of interconnection and types of transformers are so numerous that it is impossible to represent more than a small percentage of them in any system of analysis. The few shown here should serve as a basis for applying the method to other connections that may be encountered.

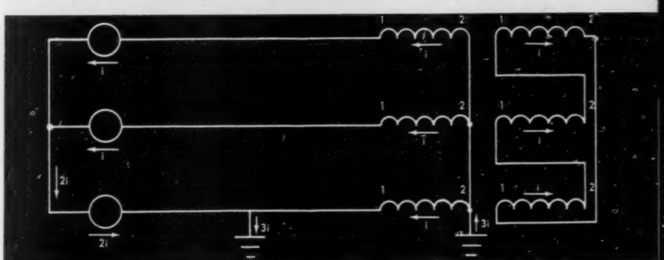
The wye-delta grounding transformer

To illustrate this method of qualitative analysis, a wye-delta grounding bank used to establish a neutral for an infinite source of wye-connected ungrounded generators is shown in Figure 3.

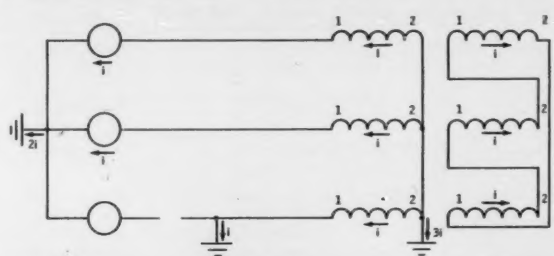
Now, if a phase-to-ground fault occurs and one current is assumed to flow in any part of the circuit, all of the currents are fixed in direction and magnitude in all parts of the circuit. For example, Figure 4 shows a phase-to-



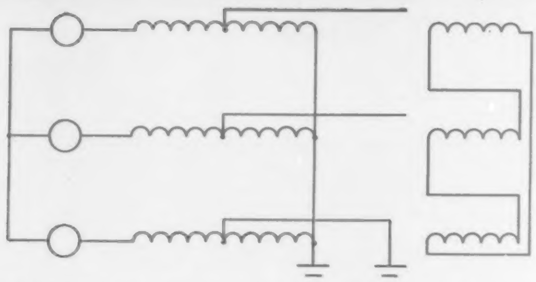
WHEN A FAULT occurs in a circuit and a specific current is assumed in one part, Kirchoff's law and magnetic balance fix direction and magnitude of currents in all other parts. **(FIGURE 3)**



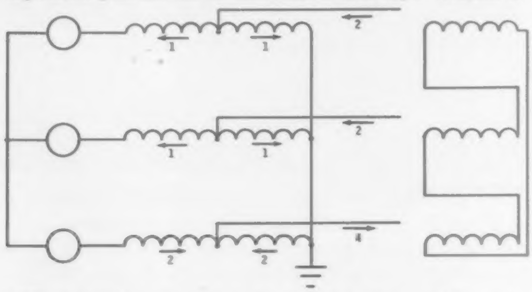
CURRENT *i* FLOWING out of the top wye winding determines relative magnitude and direction of currents in all other parts of circuit under phase-to-ground fault condition indicated. **(FIGURE 4)**



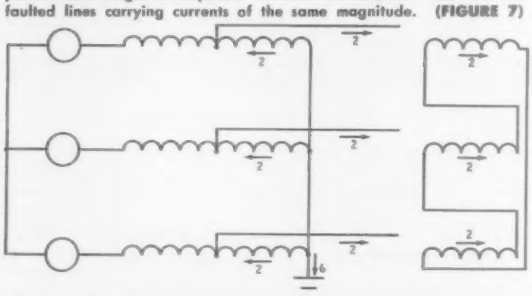
KIRCHOFF'S LAW and magnetic balance are used in the same manner as above to determine current magnitude and direction in all parts of this modified circuit with generator neutral grounded. **(FIGURE 5)**



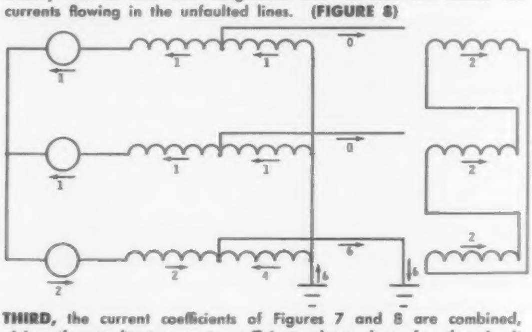
MAGNITUDE and direction of currents flowing in this 2:1 ratio three-winding autotransformer bank with grounded neutral fed by an ungrounded generator can be determined in three steps. **(FIGURE 6)**



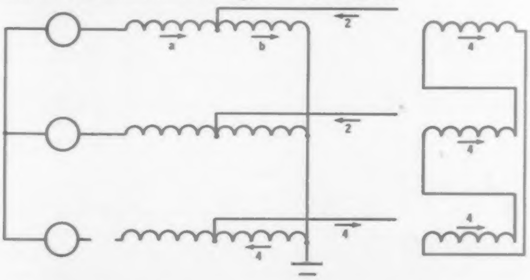
FIRST, single-phase currents on the secondary side containing only positive and negative sequence currents are selected — the two unfaulted lines carrying currents of the same magnitude. **(FIGURE 7)**



SECOND STEP is application of zero sequence currents on the secondary side so that their magnitude and direction will cancel the currents flowing in the unfaulted lines. **(FIGURE 8)**



THIRD, the current coefficients of Figures 7 and 8 are combined, giving the resultant current coefficients shown here for the circuit and fault condition shown in Figure 6. **(FIGURE 9)**



WHEN THE SUPPLY side of an autotransformer bank is fused, a similar method of analysis can be applied if the fuse on one phase blows and the fault remains. **(FIGURE 10)**

ground fault on the bottom phase. If the current i is assumed to flow out of the wye winding of the top phase of the grounding bank, then the current i must flow in the corresponding delta winding and also in other phases of the wye, assuming that the turns ratio is 1:1. If Kirchoff's law is now applied at each junction point, all of the currents in the circuit will be automatically established.

It should be noted that the relative directions and magnitudes of the current i cannot be altered without violating Kirchoff's law or the magnetic balance in the transformer. Of course, it is true that the direction of all the currents could be reversed, but this would not change the relative direction. It is also true that they may all be multiplied by a constant, but this will not change their relative magnitudes. Therefore, the assigned set of currents is the only set that can exist for the condition shown in Figure 4.

Suppose that the connections be modified by grounding the neutral of the generator and opening the phase wire between the generator and the fault. This would introduce a major change in the method of analyzing the circuit by symmetrical components. However, the same procedure is used in setting up the relative current directions and magnitudes by this method. Figure 5 shows the results of this change. Note that it is necessary to ground the generator neutral before any current can flow. The connection of the delta on the grounding bank dictates that all the grounding bank wye currents must be equal in magnitude and phase relationship. Thus with the bottom phase conductor of the generator open, it is necessary to establish the neutral connection to satisfy Kirchoff's law and make the magnetic circuit of the transformer balance. Notice that if the generator neutral is not grounded, no current can flow in the circuit shown in Figure 5.

The three-winding auto bank

Usually two-winding transformers do not have electrical connections between the windings of different voltages. Therefore, their ratio of voltage transformation may frequently be considered unity without affecting the qualitative analysis.

In the autotransformer there must be a voltage transformation. This does not mean that the turns ratio of the windings cannot be unity. In fact, the autotransformer having unity turns ratio is the easiest type to analyze. Figure 6 shows an autotransformer fed on the high side by an ungrounded generator. The autotransformer neutral is grounded, the voltage transformation ratio is 2:1, and there is a phase-to-ground fault on the secondary side. The remaining winding is shown connected in delta, which is normal practice.

On first inspection it might seem necessary to establish the currents by trial and error if the magnetic circuit is to balance and Kirchoff's law followed. This could be done, but it is not necessary if the circuit is observed and some ingenuity applied. Note first that zero sequence current cannot flow out of the generator terminals, because its neutral is ungrounded. However, zero sequence can flow on the secondary side of the autotransformer and can also circulate in the delta. Positive and negative sequence

currents can flow from the generator to the secondary side. This suggests the selection of single-phase currents on the secondary side that contain positive and negative sequence currents only, with the two unfaulted lines carrying the same magnitudes of current. Figure 7 shows how such a set of currents would flow through the bank.

Note that this set of currents does not circulate in the delta winding. To simplify the diagram, only current coefficients have been shown. As the second step in this method, apply a set of zero sequence currents on the secondary side so that their magnitude and direction will cancel the positive and negative sequence currents flowing in the unfaulted lines. This set of currents is shown in Figure 8.

Figures 7 and 8 may now be combined by adding the currents in the various parts of the circuit, taking into account their magnitude and direction. This is shown in Figure 9.

Fused supply side auto banks

Some utilities fuse the supply side of an auto bank. This presents problems in analyzing the circuit when one fuse blows and the fault remains on the load side of the bank. The method of analysis for this condition is similar to that already presented, and the process of applying the positive and negative sequence set of currents is shown in Figure 10.

With the phase open in the supply side, current will flow in the delta for the currents assumed in Figure 10. However, a problem is presented in determining the amount of current flowing in each winding of the two top phases. Since the requirements of the magnetic circuit have been established by the current flowing in the delta, and since the difference in the current flowing in the other two windings of the top transformer is the secondary line current, a simple algebraic equation will determine these currents. For example, let a be the current flowing toward the bank in the top phase and b the current flowing in the common winding of the top autotransformer. These have been shown in Figure 10 with their assumed directions. Now,

$a + 2 = b$, by Kirchoff's law

$a + b + 4 = 0$ for magnetic balance

or

$$a - b = -2$$
$$a + b = -4$$
$$2a = -2 - 4 = -6$$

$a = -3$, $b = -1$ } The minus sign merely means the arrows were assumed backward.

The zero sequence set of currents will be the same as shown in Figure 8. Therefore, combining the results of Figures 8 and 10 gives the required set of currents. Note that the results of the algebraic solution show that the two high-side line currents are the same in magnitude and direction. Therefore, it will be necessary to ground the generator neutral if fault current is to be sustained for a phase-to-ground fault on the secondary side. The results of this analysis are shown in Figure 11.

Remember that the numbers associated with the arrows are mere coefficients of the current and may all be multiplied or divided by any number. Therefore, this simply indicates that a fault on the low side will be supplied current through the good fuses if the generator neutral and the auto neutral are grounded and the delta connected on the auto bank.

Another type of single-phase fault that may occur on the autotransformer is a primary phase wire contacting a secondary phase wire. Consider the type of fault shown

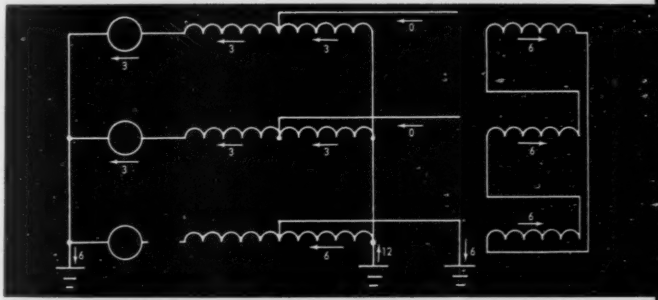


FIGURE 11

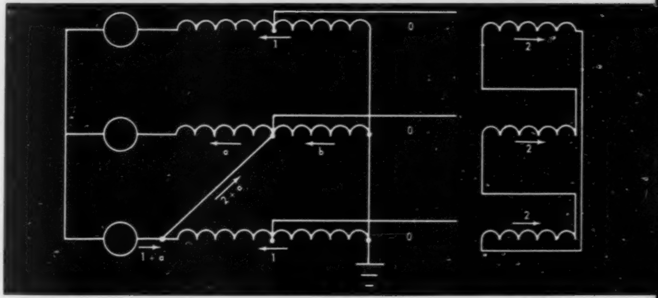


FIGURE 12

in Figure 12. The set of current vectors may be determined by assigning 1 to the bottom phase, this current flowing from the neutral to the high-side terminal, since there is no secondary side infeed. This current is transferred back into the delta, and the assignment of currents is continued as far as possible.

The assignment of current to the center phase will not be obvious. However, letters a and b may be assigned as shown and solved for in the following simple manner:

$a + b = 2$ from the magnetic circuit

$2 + b + a = a$ Kirchoff's law

$b = -2$ by solving second equation

Then $a = 4$ by substituting in first equation.

This completes the establishment of the current coefficients for the circuit given.

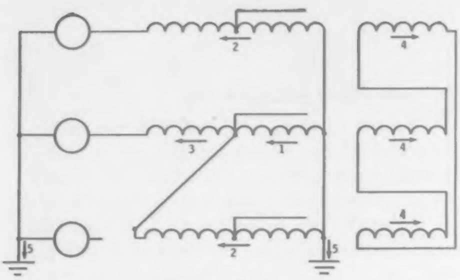


FIGURE 13

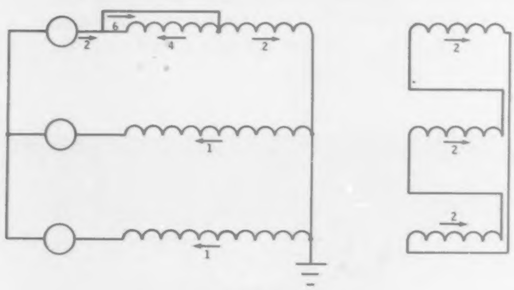


FIGURE 14

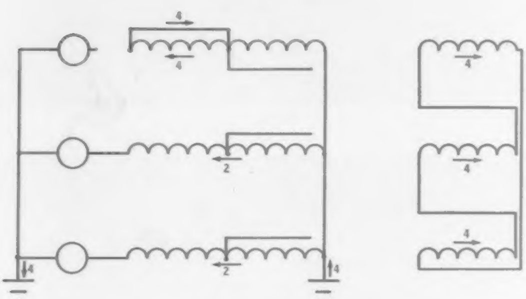


FIGURE 15

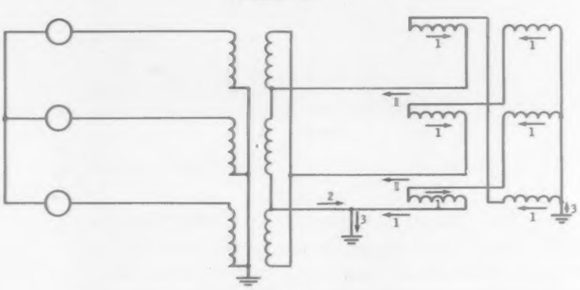


FIGURE 16

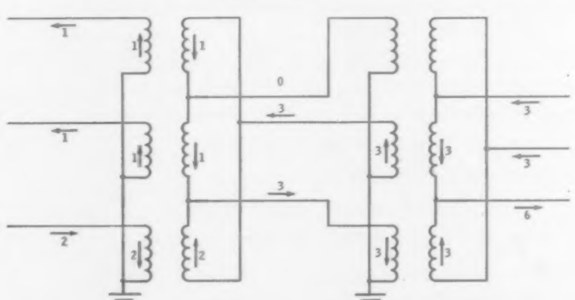


FIGURE 17

If the bottom generator phase is opened and the generator neutral grounded to provide a path, the current coefficients become those shown in Figure 13.

An autotransformer with a high-side to secondary short on the same phase will produce the current coefficients of Figure 14.

If the top generator phase is opened and the generator neutral grounded to provide a path, the coefficients of current become those shown in Figure 15.

The wye-delta bank with zigzag grounding bank

This particular connection presents a problem in the assignment of current coefficients that has not been covered. The circuit diagram is shown in Figure 16 with a ground fault.

The difficulty in this case is encountered in assigning the current coefficients that flow in the delta winding of the power bank. For example, we know that two currents enter on the top two phases, combine in the delta winding, and return on the bottom phase. The best way to solve

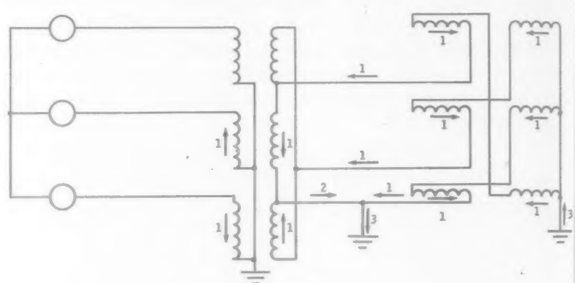


FIGURE 18

this problem is to replace the delta winding with two wye-delta banks that do not change the phase angle or magnitude of the currents. This can be done by considering all windings a 1:1 ratio and dividing the output from the final delta by 3. The method is shown below in Figure 17. The desired currents are assigned to the wye side.

Thus the method of dividing the currents in the delta shows that only two delta windings carry current for this particular condition, and Figure 16 may be completed as shown in Figure 18.

If the power supply transformer had been connected either open wye or open delta, it would have reduced the complexity of establishing the coefficients of the currents. Other constraints would also influence the solution.

The above examples serve to illustrate the problems involved in establishing current coefficients when the network is excited from one source. After this set of coefficients is established, calculating currents in all parts of the circuit in actual amperes is extremely simple. It will be noted that no examples of phase-to-phase faults were given. They are almost always easier to establish than the examples given. If the above procedure is followed, no difficulty should be encountered.

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